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Bachelor Thesis

Numerical Analysis of Wave Propagations on WWI Trenches

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1. INTRODUCTION

1.1ABSTRACT

Trenches were an interesting and innovative way of doing war born during WWI. They allow almost full protection against straight shoot weapons, but they have it weakness against parabolic shoot weapons like hand grenades and mortars.

But even if they supposed an advantage, during this paper it will be tried to found out if this advantage were optimized or not. That is, were these trenches built in the best possible way to minimize the effects of an explosive arriving to them?

Using the computational methods that are available nowadays, this question will be solved. By simulation means, first a model case will be analyzed in order to see the behavior of blast pressure waves inside this trench. Later some modifications will be implemented around this model case in order to see if these modifications imply a benefit or a hazard.

There are two main modifications that will be applied to the model case. In the first case, just the location of the initial explosion will be varied under constant trench geometry. This is done to check if there is some relevant influence on the mortality of the explosion depending on where it occurs. In second place, the geometry of the trench will be varied. Variations will be done in the three dimensional directions. The height will be increased and decreased, as well as the length and width.

Once all these cases have been analyzed, it is also important to wonder about the validity of the results obtained. In order to solve this point, a sensitivity analysis will be done, by refining the used mesh and checking the real influence of the mesh on the results.

To sum up the study, a brief conclusion section will be written in order to summarize all the points and information gathered through this report.

1.2 MOTIVATION

Since the very first moment my tutor exposed me the main lines of this study, I decided to work with him in order to find the most accurate solution that our resources allow. In order to better understand this decision, I will start with a brief historical summary.

The concept of a trench was born during WWI, in particular on the "Battle of Marne", that took place between the 5 and 12 of September of 1914. This battle supposed a huge change in war strategies of the time. Until that moment "War of Movements" had been practiced. That is, two armies that look for each other and fight in the same place.

At this moment, a new way of doing war appears which is called "War of Trenches". This new manner of fighting can be defined as a war model in which both armies place themselves on opposite locations. At these locations trenches were dug on the ground. From these trenches, armies can shoot their enemies from a safety position.

For the problem that will be studied on this work, it is of interest to know more in detail the structure and dimensions of these trenches, in order to adjust the simulations to the reality. Different ways of building the trenches existed, but the most common one was to dig three parallel frontal lines joined by inter-trenches or communication trenches. This kind of trench is shown on Fig. 1

Fig. 1 – WWI Trench Top View. (Public Domain Image)

It is also interesting to mention that these frontal trenches were not made straight. They had certain curvature and zig-zag shape. Building them in this way they avoid that an enemy soldier located inside the trench can have complete vision of the trench. At the same time the protection against explosives was increased.

Cross section geometry of this kind of trenches is also of interest for our study. The geometry was always the same however the dimensions could vary slightly. This geometry can be appreciated on Fig.2

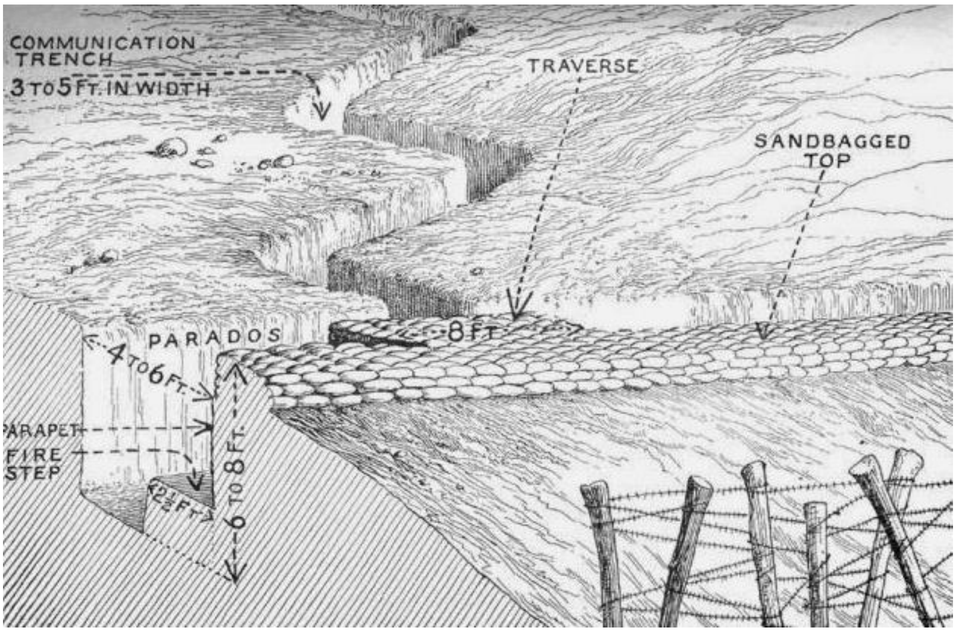

Fig. 2 – Trench Cross Section Geometry and Dimensions (Public Domain Image)

In this new way of doing war, weapons with straight shooting lost almost all its effectivity. Parabolic shoot weapons (mortars, hand grenades) took a big relevance since they were more efficient on crossing the enemy defenses.

In Fig.3 it is possible to see the two most common hand grenades used during WWI. To the left, the favorite of France, Grenade F1 with higher amount of explosive. To the right, the grenade “Model 24” widely used by Germans. This one, due to its innovative structure can be thrown further.

t

Fig. 3 – Most common Hand Grenades (Public Domain Image)

1.3 OBJECTIVES

So, at this point there are no doubts about how efficient the trenches were against straight trajectory weapons. But one may think: How effective were these trenches against parabolic trajectory weapons?

During this whole paper, the answer to this question will be searched. It will be tried to clarify if the trenches were optimized to minimize the injuries done on human been by this kind of weapons. In order to reach a conclusion, several simulations will be done, first on a trench modeled as close as possible to reality and then simulations where both geometry and explosive location were varied, in order to check under which situations the effects are less critical.

Also, the point in the trench where the less critical effects appears, will be searched by studying pressure wave propagation through the bunker, pressure time history on local points of the bunker as well as the accelerations produced by these pressures. Accelerations will not be studied directly, but through a parameter called Head Injury Criteria (HIC), better defined in next sections.

Finally a sensitivity analysis will be also done in order to have an idea of the validity of the results obtained and how accurate the conclusions are.

1.4 BUDGET AND PLANNING

In this section a brief analysis of temporal and monetary planning is going to be done. First temporal planning will be treated.

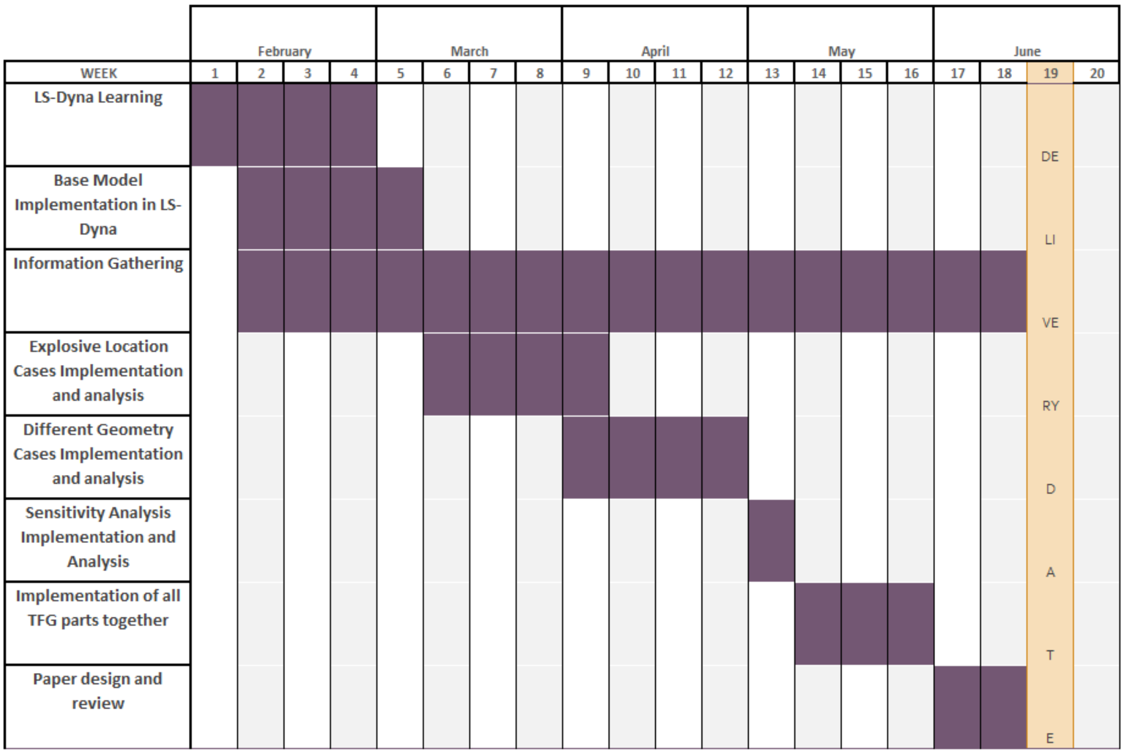

Fig. 4 – Gantt Diagram for the present project

The planning followed can be seen in Fig. 4. As it can be seen, this project has last four and a half months. First month was entirely dedicated to getting familiar with LS-Dyna software, by trying to reproduce the model case completely from zero. At the same time some information (state of the arte, blast analysis…) was started to be gathered.

Information gathering was, in fact, a task that lasted from the begging to the very end of the project, since at every step it was moved forward new information was required.

Once LS-Dyna and its particular working process were better understood, new simulations were done. First, almost the whole month of March was required to simulate and analyze the cases where explosive location was varied. Later, April weeks were used to simulate and analyze the cases where the geometry of the trench was varied. Since nothing new had to be implemented for the sensitivity analysis (except from the mesh of course) only one week was required to simulate and analyze this case. Finally all the analysis was needed to be implemented together as well as some review, giving the same format to each of the parts. Basically, what is all the design process of the report took some more time than the one expected.

All these days were not completely devoted to developing this work, of course, but an average of 4 hours per day was working hours. That makes a total of:

$$4\,\frac{hours}{day} * 7\,\frac{days}{week} * 4\,\frac{weeks}{month} * 4.5\,month = 504\,total\ hours\ spent$$

This data is also required in order do an estimation of the monetary costs of the project. The main contributors to expenses are:

- Total LS-Dyna License 1000 €
- Average Computer 500 €
- Average Novice Engineer Salary 9 €/h
- Money Spent on Novice Engineer 4536 €
- Other minor expenses (light, paper…) 100 €

Adding all this components together end up on a final average project price of 6136 €. These are (in average) the monetary and temporal expenses of this project.

2 ANTECEDENTS

In this section, the engineering knowledge behind the computations performed by LS-Dyna software will be exposed

2.1 BLAST THEORY

A good starting point to explain what a blast is and how it behaves is to look at the pressure behavior at a particular point of the space after a blast. When doing this, the result obtained is always similar and summarized in Fig. 5

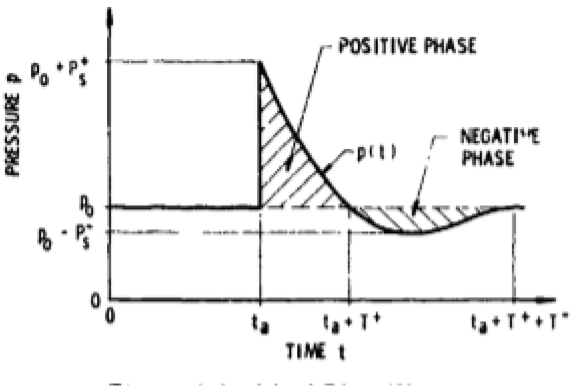

Fig. 5 – Pressure behavior at point after an explosion. Taken from [6]

At the moment of the explosion "t_a" an almost instantaneous increase of pressure can be seen. This is part of the blast is known as pressure peak and it corresponds with the main pressure shock wave of the explosion. Once this pressure front has passed the point, pressure tends to recover its initial value. In this process it undergoes two different phases. Positive and negative phases.

These two phases, historically, have been treated separately. Several equations have been developed to simulate the positive phase, being probably the most used one the "Modified Friedlander's Equation" that can be seen down here:

$$P(t) = P_0 + {P_s}^+(1 - t/T^+)e^{-bt/T^+}$$

Where "b" is called the "Decay Coefficient" and is obtained from experimental data.

To simulate the negative phase, the most common expression is the "Brode Equation", summarized below:

$$P(t) = P_0 - {P_s}^-[(t/T^-)(1 - t/T^-)e^{4t/T^-}]$$

However this representation of the positive and negative phases of a shockwave is only applicable for ideal waves propagating in free air. In reality there are always deviations and additional effects related to the existence of different propagating media.

When a blast occurs close to wall (in the case that will be studied, it occurs between three different walls), different effects and behaviors can be observed.

Ground effect is probably the most common. If the pressure evolution is analyzed close to the ground or wall when an explosion occurs, a first smaller pressure peak will appear as it is shown in Fig. 6. This first peak does not correspond to any pressure wave. At the moment blast occurs, air is compressed due to the existence of the ground, that does not allow air to propagate through it creating an increase in pressure and temperature reflected on the first figure pressure peak. The second and higher pressure peak corresponds to the main pressure wave of the blast as in the case before.

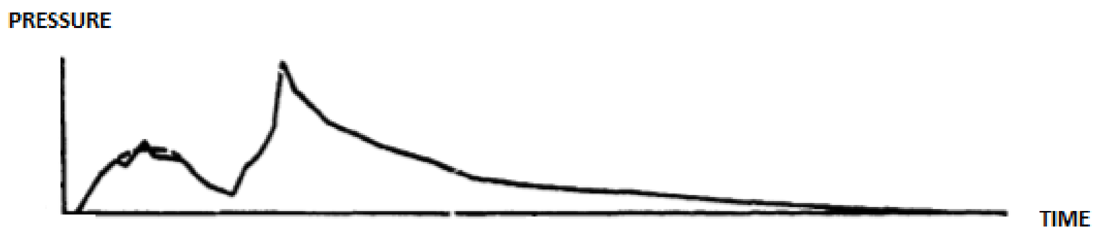

Fig. 6 – Ground effect of a blast. Taken from [6]

On the other hand, along the whole study done in this work, also several wave reflections will appear. Reflections occur when a pressure wave encounter a rigid wall through which it can't propagate. So pressure wave bounces on this wall and changes the downstream properties of the air.

The easiest reflection that may appear is the normal reflection, represented on Fig. 7

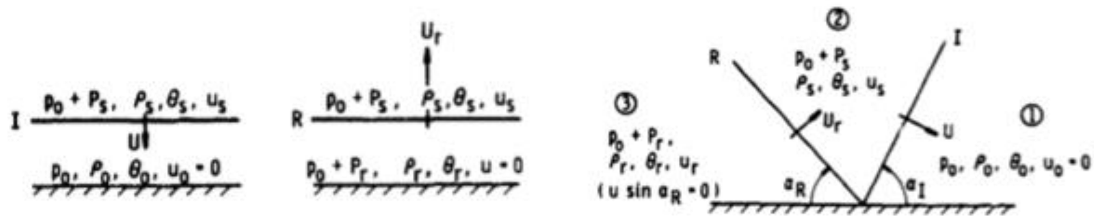

Fig. 7 – Pressure wave normal and oblique reflections. Taken from [6]

In case of normal reflection, the pressure wave just bounces on the wall and start propagating in the opposite direction. The air left downstream by the reflected wave present higher pressure than the still air before the wave. Oblique reflections act similar but the direction of the reflected wave is not fixed, but depends on the direction of the incident wave. However the effects they produce on the air are the same.

In the problem that will be treated here, the presence of this secondary waves or reflected waves will appear as secondary pressure peaks on the pressure-time plot. Since the explosion occurs in an almost closed space, the amount of reflected waves in this problem is high.

2.2 HEAD INJURY CRITERIA

During the whole work and for all the cases under analysis the Head Injury Criteria, or HIC abbreviated is going to be calculated. Therefore it seems reasonable to dedicate some time to explain what it is and how is it calculated.

It is basically a parameter that measures the effect of an impact on humans head. This parameter is widely used in crash test analysis to see the mortality of each of the crashes. An accelerometer is placed in the center of gravity of the dummy's head, and the acceleration records are used to compute the HIC.

Even if this is its major and well known use, the parameter checks the magnitude of acceleration or deceleration and the time interval in which it occurs so it is also applicable for the cases that are studied here. Since the explosion will create a sudden acceleration, similar to that of a car crash. The parameter is defined as follows:

$$\mathrm{HIC} = (t_2 - t_1)(\frac{1}{t_2 - t_1} * \int_{t_1}^{t_2} a(t)dt)^{2.5}$$

As the HIC value increases, also does the hazardous effect of an impact. So what can be seen just from a quick view is that the higher the accelerations the impact produces, the more dangerous effects of the impact. Also, the lower time interval in which this acceleration occurs, again the more dangerous effects of the impact on human being.

There exist some experimental tables that define the effects of an impact depending on the HIC value. This table is shown below:

AIS	*Injury entity*	*Fatality percent*	*HIC index values ranges*	*Head Injury*
0	None	0	0 - 134	none
1	Minor	0 - 7	135 - 519	Headache or dizziness
2	Moderate	7 – 18	520 - 899	Unconscious less than 1 hour; linear fracture
3	Serious, without life danger	18 – 42	900 - 1254	Unconscious 1 to 6 hours Depressed fracture
4	Severe, with life danger	42 - 70	1255 - 1574	Unconscious 6 to 24 hours; Open fracture
5	Critical (uncertain survival)	70 – 87	1575 - 1859	Unconscious more than 24 hours; large haematoma.
6	Fatal	87 - 100	> 1860	Non-survivable

Table 1 – Head Injury Criteria Limits. Taken from [4]

As it can be seen once the HIC exceed 1860, the chances of surviving are zero.

2.3FEM AND MMALE

Since the problem under analysis is too complex to be analyzed analytically, the use of numerical simulation is needed. In this case “LS-Dyna” commercial software was selected to be the tool for the numerical simulations.

The software application used for the analysis of the problem presented in this work is based on Finite Element Method. As it is well known, FEM is used to face continuous physical problems in an easier way. The continuous medium is divided in to several discrete elements. The corresponding equations are applied to each of these elements and the required output is obtained also at each of these elements, so globally, results can be extrapolated to be the results of the continuous problem.

Of course, since it is an approximation to reality, this method presents its limitations. In this work the main problem faced with Finite Element Method is to decide when the mesh is refined enough in order to have reliable results. This point will be treated in section 5, sensitivity analysis.

In particular for this study study it is of interest what is called Multi-Material Arbitrary Lagrangian Eulerian method. A method present in LS-Dyna software. This method is a combination of Eulerian and Lagrangian formulation. Eulerian formulation and calculations are done by fixing the reference frame at specific locations and studying at those points the problem. On other hand, for Lagrangian formulation the reference frame is moving with the particles under study. ALE (Arbitrary Lagrangian Eulerian) formulations take a combination of both that allows obtaining better results.

In order to do so what LS-Dyna does is divide each computational step in two different sub-steps. During the first one the mesh translates at the same time that the material does. During second step, mesh remains fixed and is smoothed in order to adjust to the part under study and to minimize distortion. A graphic representation of this method can be appreciated in Fig. 8.

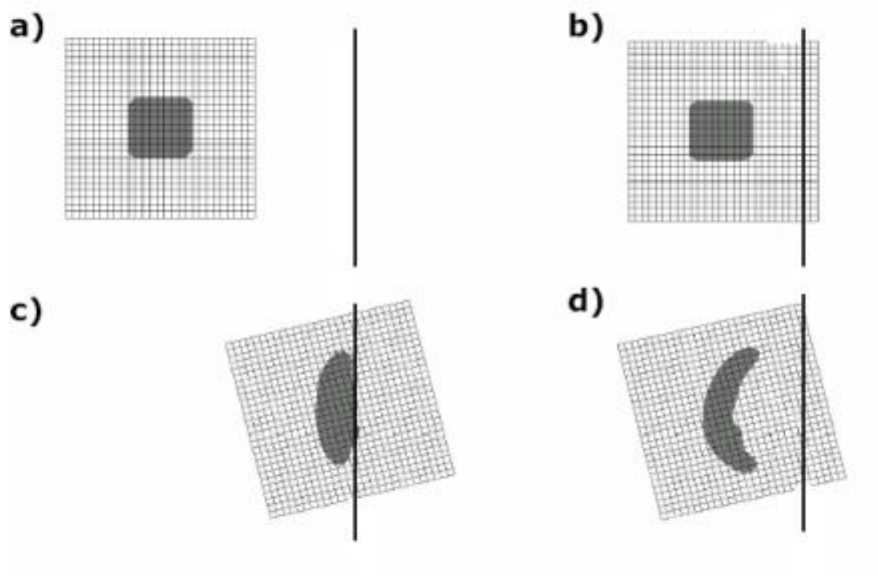

Fig. 8 – Multimaterial Arbitrary Lagrangian Eulerian Method. Taken from [5]

3. DESCRIPTION OF THE MODEL

In this section the geometry and physical characteristics of the model under analysis will be exposed. Unless otherwise stated in the corresponding section, this is the data and characteristics that are going to be used through all the following analysis.

All the models are composed of 3 different elements:

- The solid walls of the bunker.
- The air contained in the bunker.
- The explosive.

These three elements are common to all cases, and they are simulated in LS-Dyna in the same way.

3.1 BUNKER CHARACTERISTICS AND DEFINITION

In Fig. 9 it is possible to appreciate a view of the geometry. Have in mind that this figure only represents a quarter of the bunker. As it will be explained later, symmetry conditions are imposed on plane of sides E-G and plane of sides B-D.

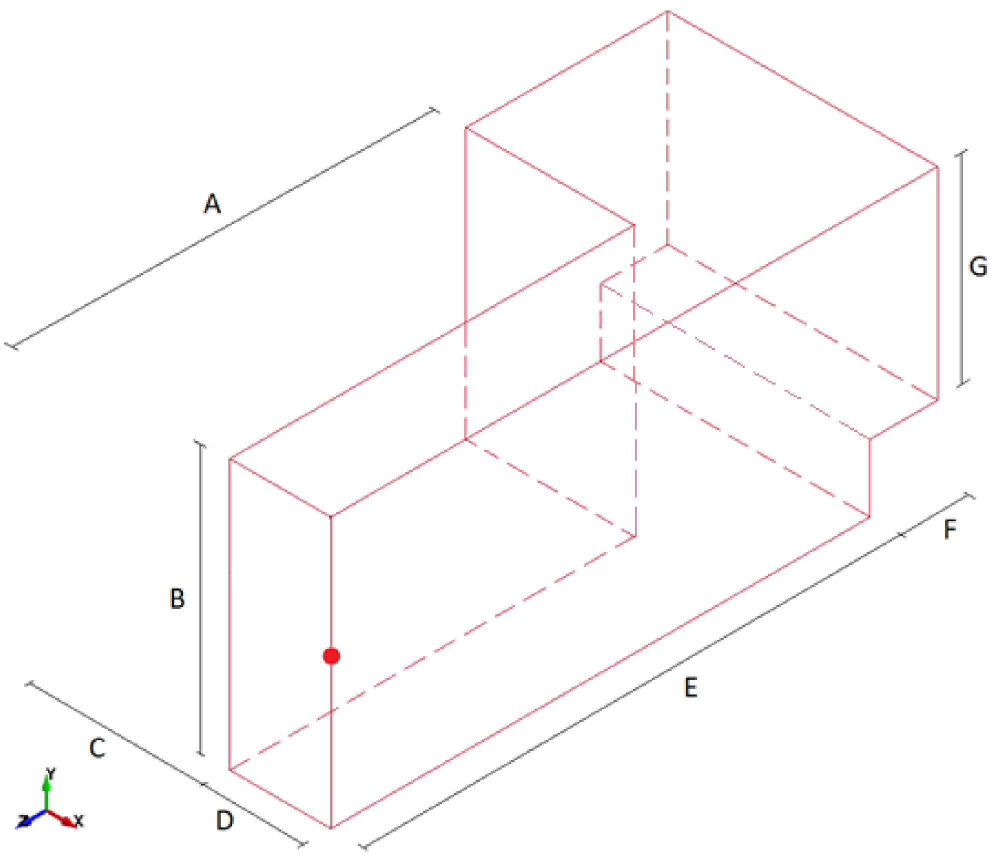

Fig. 9 - Bunker Geometry Definition

The dimensions of this geometry are summarized in Table 1. Please note that units are millimeters.

Bunker Dimensions (mm) [Base Model]						
A	B	C	D	E	F	G
3000	2000	1250	750	4000	500	1500

Table 2 –Bunker Geometry Dimensions

Different parts of this geometry have different characteristics. Some parts are defined as rigid walls, other ones as non-reflecting surfaces and others as symmetry surfaces. This is all done in LS-Dyna through the “BOUNDARY” tab.

Fig. 10 shows marked in black the surfaces modeled as “NON_REFLECTING”

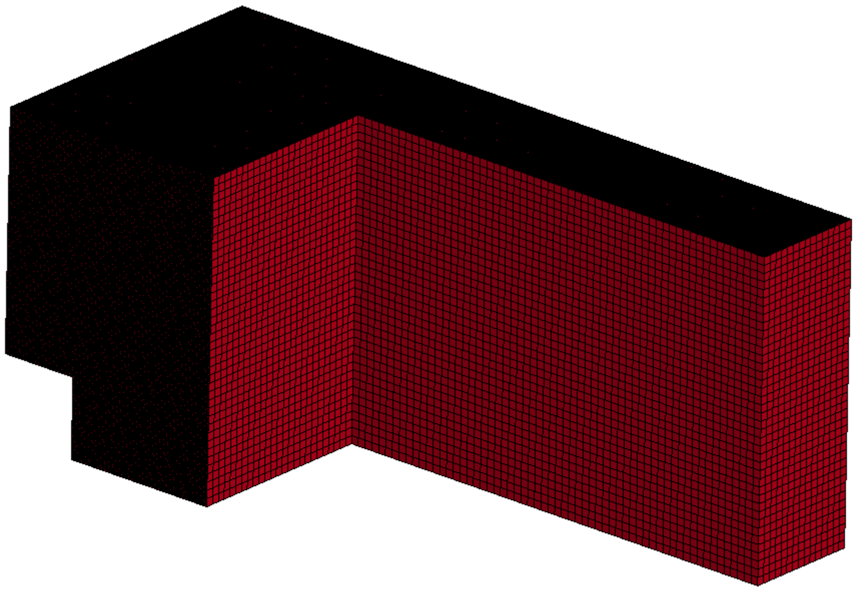

Fig. 10 – Non-reflecting surfaces

This “NON_REFLECTING” condition is basically used to simulate the absence of a wall in those surfaces. In a real bunker, soldiers will be standing up on the bunker step and shooting to the enemy at ground level. That is why it makes no sense to simulate a wall or symmetry on the upper part of bunker. In the same way, as explained in the introduction, the bunkers were made by the union of several ramifications. The bunker may continue through the lateral black surfaces hundreds of meters. So, this condition allows simulating these situations, by letting the waves leave the domain under analysis.

Fig. 11 shows all the rigid walls of the model from left to right, in green, yellow and brown.

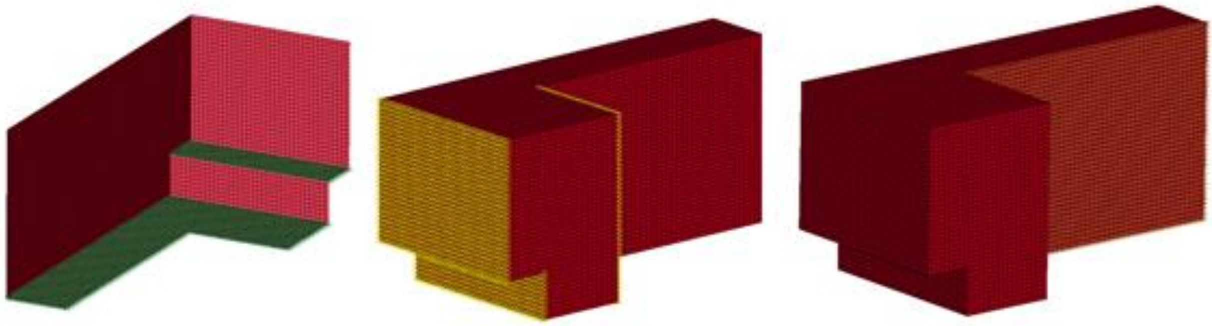

Fig. 11 –Wall surfaces

The restriction that defining these surfaces as walls implies is basically that movement in the normal direction to each of the walls is not allowed. In the practice, that means that air can't cross these surfaces. It will bounce back or slide in the direction of the wall.

Finally Fig. 12 shows the symmetry surfaces from left to right in red and blue.

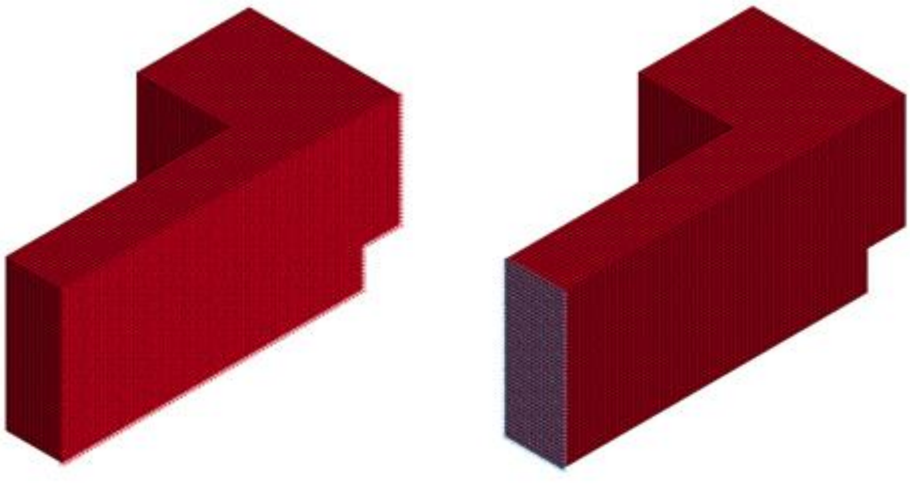

Fig. 12 –Symmetry surfaces

At these surfaces, movement in the normal direction is not allowed. Additionally only rotation about the axis normal to these surfaces is allowed. It basically a wall as the previous seen but it does not allow any rotation through its surface.

3.2 AIR MATERIAL MODEL

Bunker geometry is full of air. Air simulation in LS-Dyna is done through a material option called "MAT_NULL". This option allows us to define several characteristics of the material, since it can be used to simulate more materials apart from air or gases in general. But for defining air, only 3 parameters are relevant and they are defined in the Table 2.

Parameter	Density	Pressure Cut-Off
Value	1.23 kg/m^3	-10000 MPa

Table 3 – Air Characteristics

Pressure Cut-Off shall be defined in order to allow the material under simulation to cavitate. This LS-Dyna option can be used to simulate not only gases, but also fluids where cavitation process occurs. However in "MAT_NULL" tab, this is a mandatory field even if we are simulating a gas. As it is stated in Refs. [1], [2] and [3]. LS-Dyna simulates cavitation when pressure goes below the pressure Cut-Off value. So by setting a really low pressure Cut-Off value, it is possible to ensure that cavitation effect does not appear in our air model, since this would not make sense at all.

Equation of state also has to be defined. It was done through an option called "EOS_LINEAR_POLYNOMIAL". This is basically an equation linear in internal energy.

$$P = C_0 + C_1 * \mu + C_2 * \mu^2 + C_3 * \mu^3 + (C_4 + C_5 * \mu + C_6 * \mu) * E$$

Using this equation, pressure is computed as a function of the actual density since:

$$\mu = \frac{\rho - \rho_0}{\rho_0}$$

Where ρ_0 is the reference density used in "MAT_NULL" tab, that is, 1.23 kg/m^3. In LS-Dyna Manual, Refs [1], [2] and [3], it is stated that this equation can be used to model a gas with the gamma law equation if:

$$C_0 = C_1 = C_2 = C_3 = C_6 = 0$$

and

$$C_4 = C_5 = \gamma - 1 = 0.4$$

where

$$\gamma = \frac{C_p}{C_v} = 1.4 \quad (at\ T = 15ºC)$$

After applying all these changes, the equation of state becomes just the gamma-law equation. Note that E has units of pressure, and it is the product of internal energy of the air and the reference density

$$P = (\gamma - 1)\frac{\rho}{\rho_0}E = (\gamma - 1)\rho u$$

Then, in order to start computation two additional parameters are needed in LS-Dyna. First the initial internal energy of air per unit volume, that at 15ºC is 258 kJ/kg. Second the relative initial volume of air, but compared to the reference volume as:

$$V_{rel,0} = \frac{V_{t=0}}{V_0} = 1$$

3.3 EXPLOSIVE MATERIAL MODEL

Simulation of the explosive in LS-Dyna is done through two different options:

- "MAT_HIGH_EXPLOSIVE_BURN", where physical characteristics of the explosive are defined
- "INITIAL_VOLUME_FRACTION_GEOMETRY", where dimensions and location of the explosive are defined.

The explosive selected is known as RDX and its characteristics are summarized in the table 3

Parameter	Density	Detonation Velocity	Chapman-Jouget Pressure	Explosive Volume	Explosive Dimensions
Value	1601 kg/m^3	8193 m/s	28000 MPa	250000 mm^3	50x50x100 mm

Table 4 – Explosive Characteristics

Explosive does also need an equation of state. This was model in LS-Dyna through the option "EOS_JWL", which stands for Jones-Wilkins-Lee equation of state for explosives. The expression is the following:

$$P = A\left(1 - \frac{\omega}{R_1 * V}\right) * e^{-R_1 * V} + B\left(1 - \frac{\omega}{R_2 * V}\right) * e^{-R_2 * V} + \frac{\omega * E}{V}$$

The value of the several coefficients of the equation are summarized in table 4

Parameter	A	B	R1	R2	ω
Value	609800 MPa	12950 MPa	4.5	1.4	0.25

Table 5 – JWL equation coefficients

As it happens in the case of the air, also initial conditions of detonation, energy per unit volume (E_0) and initial volume (V_0) shall be defined in order to start the simulation. These values are $E_0 = 9 * 10^6$ kJ/(kg K m^3) and the initial volume the one of the section defined, that is V_0 =0.25 *10^{-3} m^3 .

4. RESULTS

Now that all characteristics of the numerical model under study have been defined in Section 3, the results obtained from the simulation are going to be shown in the next pages.

In all the following different results, the same scheme is going to be followed. First, a qualitative analysis of the pressure propagation will be done. Second, a quantitative analysis of the pressure at different points of the model will be studied. As a final step, the Head Injury Criteria (HIC) is going to be analyzed.

4.1 BASE MODEL ANALYSIS RESULTS

4.1.1 QUALITATIVE ANALYSIS OF PRESSURE PROPAGATION

LS-Dyna software, allows having a visual understanding of the pressure waves distribution inside the bunker during the simulation period of time. Next set of images will show this behavior for the base model geometry and explosive.

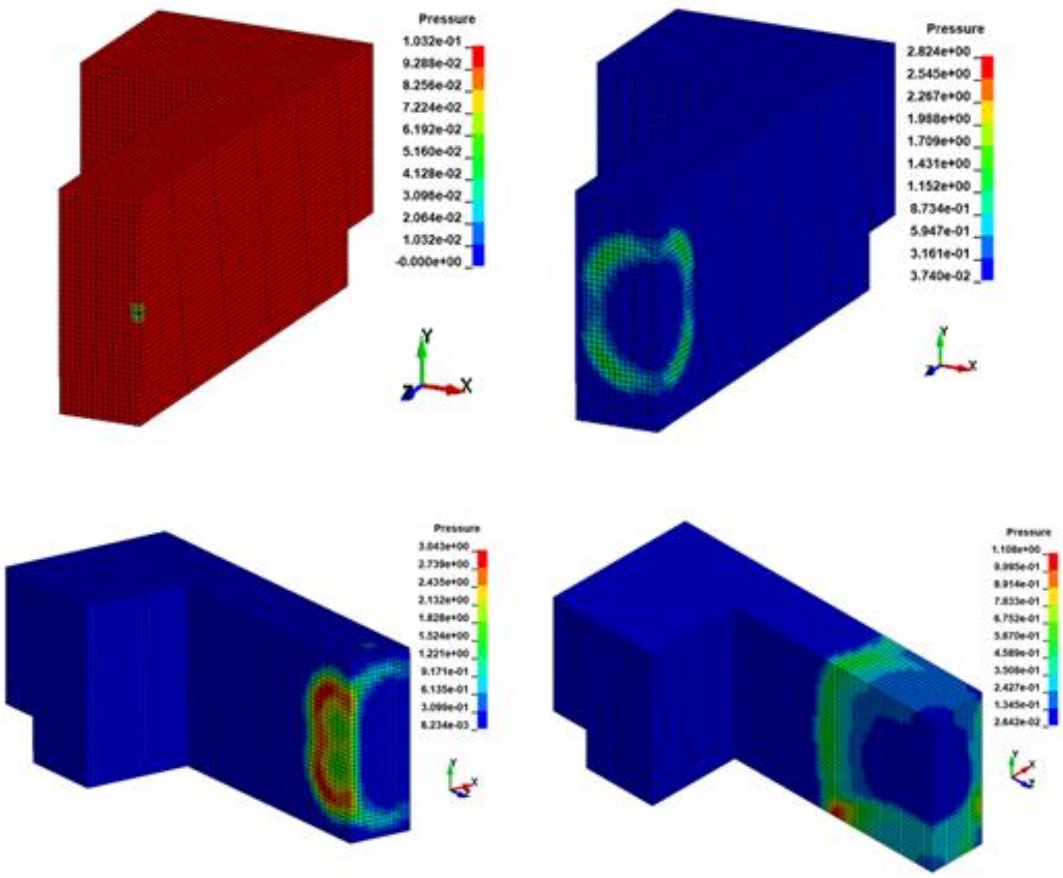

Fig. 13 – Base Model Pressure (MPa) Propagation. Step 1

As it can be appreciated in Fig. 13.a, before explosion pressure is kept uniform along the whole bunker at a value of 0.1 MPa (1 atm). Once explosion occur (Fig. 13.b), pressure initially increases by one order of magnitude and it starts to propagate radially through the bunker. Later at Fig. 13.c, pressure wave collides with the bunker side wall, increasing pressure by a factor of 2-3. Since air can't continue its expansion through the wall, air particles start to accumulate in this region therefore creating the increase in pressure mentioned before. Pressure front then, continues its expansion towards the inside of the bunker. A pressure peak, as it can be seen in Fig. 13.d, starts to appear close to the bunker floor.

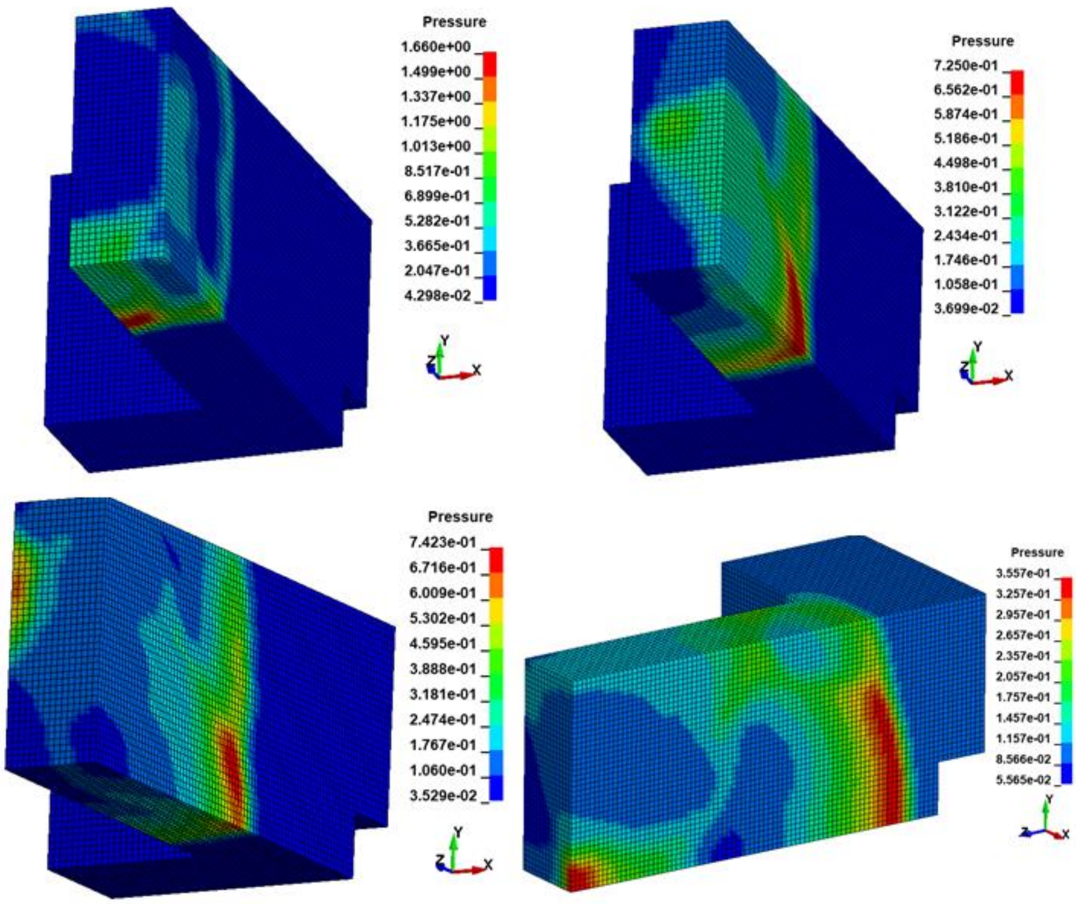

Fig. 14 –Base Model Pressure (MPa) Propagation. Step 2

Fig.14.a is a bottom view of the previous step. The sequence of Fig.14.a and Fig.14.b shows how the pressure peak developed at bunker and close to the floor now propagates towards the center of the bunker. In Fig. 14.c and Fig.14.d it can be appreciated how this pressure wave starts growing and increasing its value until the moment of the collision against the step of the bunker.

It can also be a seen in Fig.14.d the appearance of a secondary pressure peak close to the point of the initial explosion. This fact is due to the reflected secondary pressure waves, which under this particular geometry end up creating this pressure peak at that specific location.

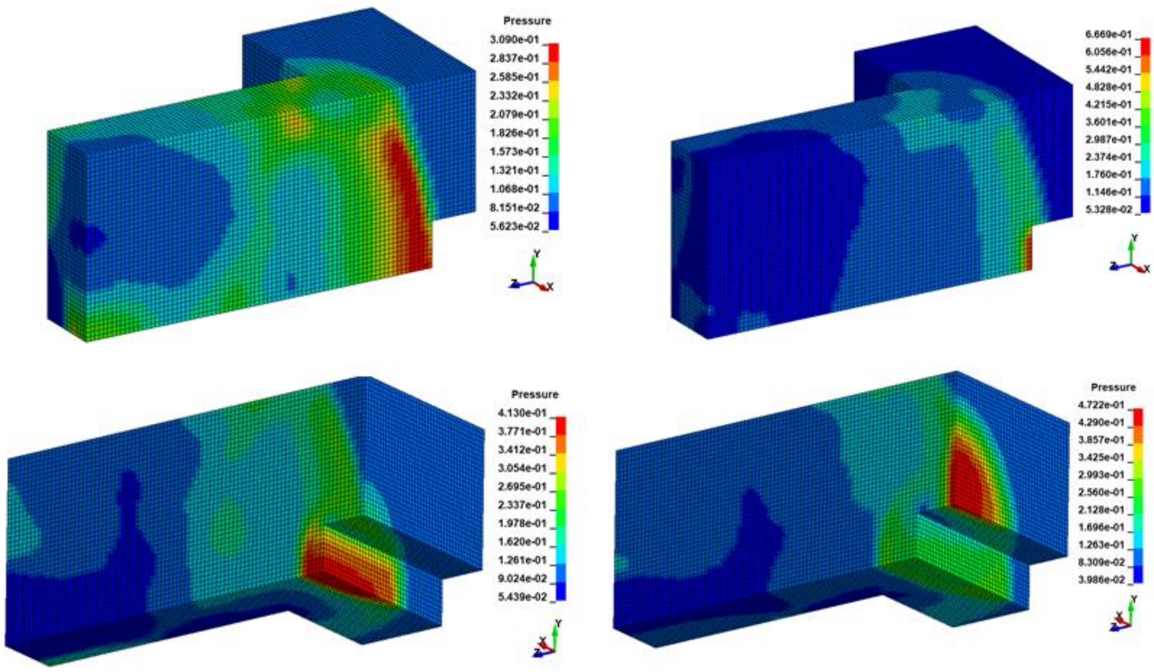

Fig.15 – Base Model Pressure (MPa) Propagation. Step 3

Now the primary wave arrives to the step. At the moment they come into contact, shown in Fig. 15.b, the pressure of the air colliding against the lower part of the step suddenly increases. It doubles its value at the moment of contact. Then it starts to expand to the lateral of the bunker and it decreases its pressure back again to a value close to that it has before colliding. Then, in Fig. 15.d, the primary pressure shock arrives to the higher part of the step, to the end wall of the bunker, and air pressure suddenly increases due to the same reason as before, but this time the increase in pressure is lower. This is due to the fact the pressure wave is colliding against a higher area, so air can expand easier, therefore pressure does not suffer such increase.

It is also interesting to note that the secondary pressure peak slowly vanishes, having no major impact close to the primary one.

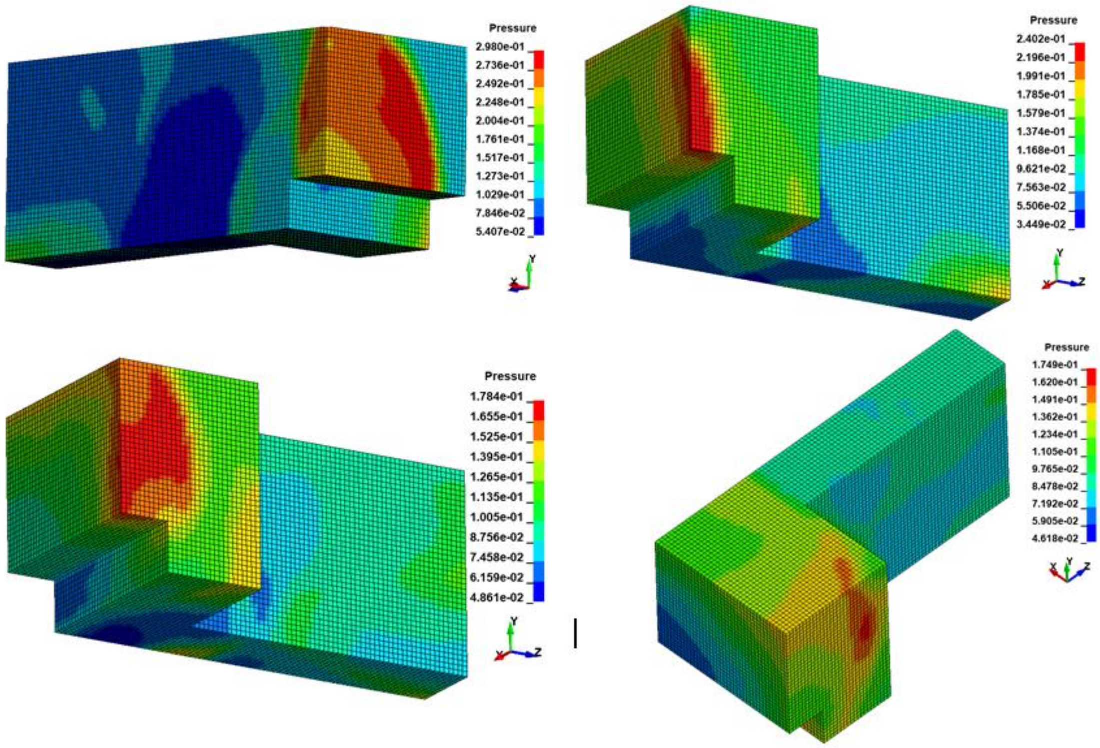

Fig.16 –Base Model Pressure (MPa) Propagation. Step 4

In Fig. 16.a is possible to better appreciate how the pressure wave expands towards the lateral of the bunker ramification. As it expands, its magnitude decreases. It propagates until it encounters the lateral surface, as it can be seen in Fig. 16.c. However remember that this surface was not defined as a wall, but as a "Non-reflecting" surface, therefore pressure wave is not colliding against anything. Finally, the wave starts to disappear and pressure starts to homogenize inside the bunker. It will follow this behavior until equilibrium is reached inside the bunker.

It is interesting to see that the location where the maximum pressure is achieved (apart from close to the moment of the initial explosion) is at the lower part of the step. So one may think this place is the most dangerous one. A person sitting there will have the higher chances to suffer critical injuries, even death. However later in this section, Head Injury Criteria (HIC) will be analyzed. This parameter measures how hazardous an impact is. HIC measurements are not using the pressure value, but also the acceleration. Using this value, we will be able to confirm is this spot is really the most dangerous one or not.

At this point, the qualitative evolution of the pressure wave has been analyzed, but now it will be interesting to have a look at the behavior of pressure magnitude in some fixed points of the bunker volume.

4.1.2 QUANTITATIVE ANALYSIS OF PRESSURE

The next figure shows the set of points of the volume that are under study:

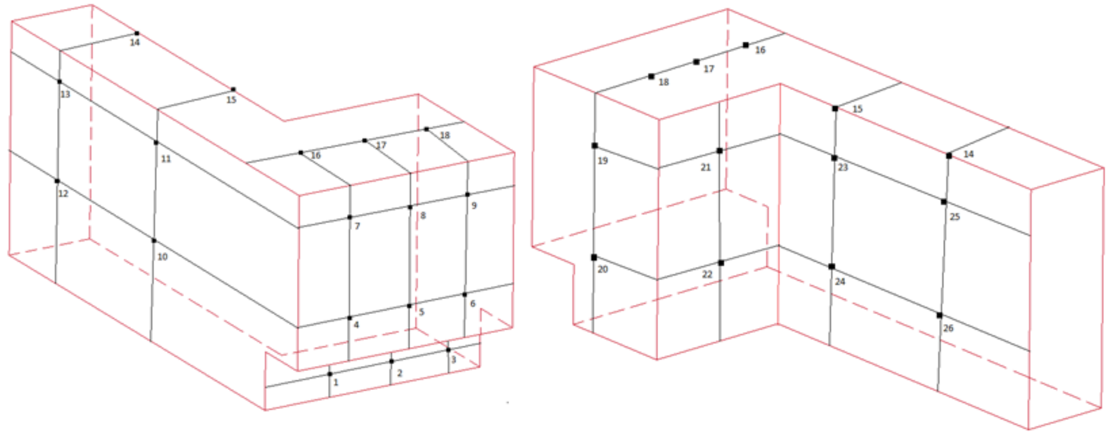

Fig. 17 – Distribution of points under analysis

At the moment it was needed to decide which points will be studied, it was thought that all zones of the bunker volume are interesting to study. So the distribution of the points was made covering all zones in a homogeneous way. But it was also though, that for HICs (Head Injury Criteria) study, it would be interesting to have several points at the height where the head of a person would be. That is why points are slightly displaced upwards and no points can be found at bunker's floor.

Points were placed in cross section sets. These sets are summarized in table 5 from the closest to the explosion point to the furthest one.

Set Number	Points inside the set
1	12, 13, 14, 25 ,26
2	10, 11, 15, 23, 24
3	21, 22
4	16, 17, 18, 19, 20
5	1, 2, 3, 4, 5, 6, 7, 8, 9

Table 6- Sets of Points under Study

The analysis will be done in the same order as the pressure front propagates through the bunker. That is, sets 1, 2, 3, 4 and 5 in this order.

In Fig. 18 it is possible to appreciate the time history of pressure on set 1 of points. Note also that Fig. 18.a studies the points located at the middle of the bunker. On the other hand, Fig. 18.b analyses the points located at the wall of the bunker. Both at the cross section located closest to the initial explosion.

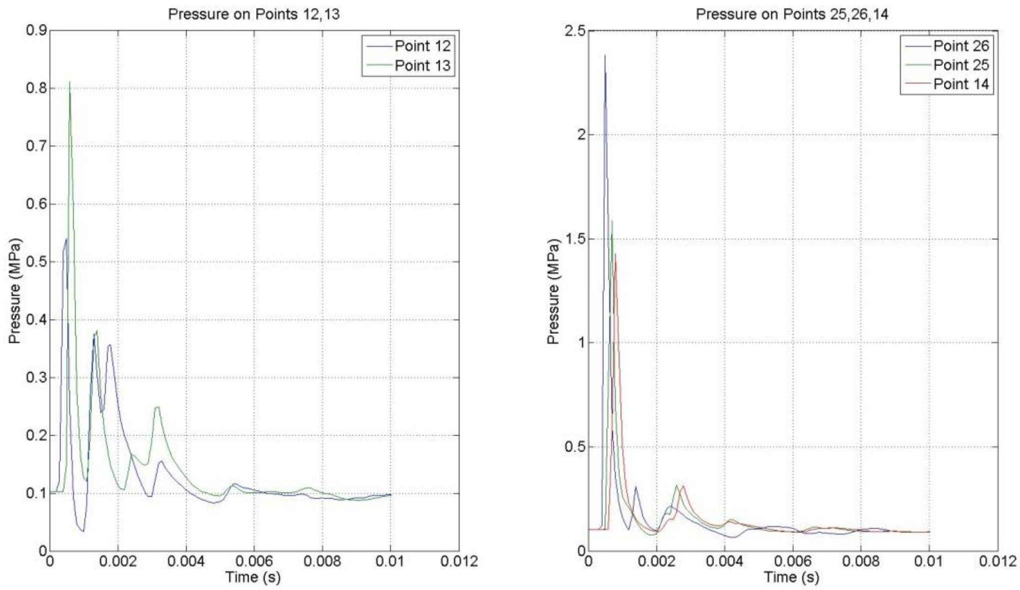

Fig.18 – Pressure Behavior at Points of Set 1. Model Case

In both cases, pressure suddenly increases at the moment of the explosion, but note that close to the wall this increase is 2 or even 3 times the increase in the middle of the bunker. Since pressure wave encounters here a rigid wall through which it can't propagate, and therefore velocity is suddenly decreased, the energy of the wave is traduced into a much higher increase of pressure. This fact can be seen on Fig. 19.

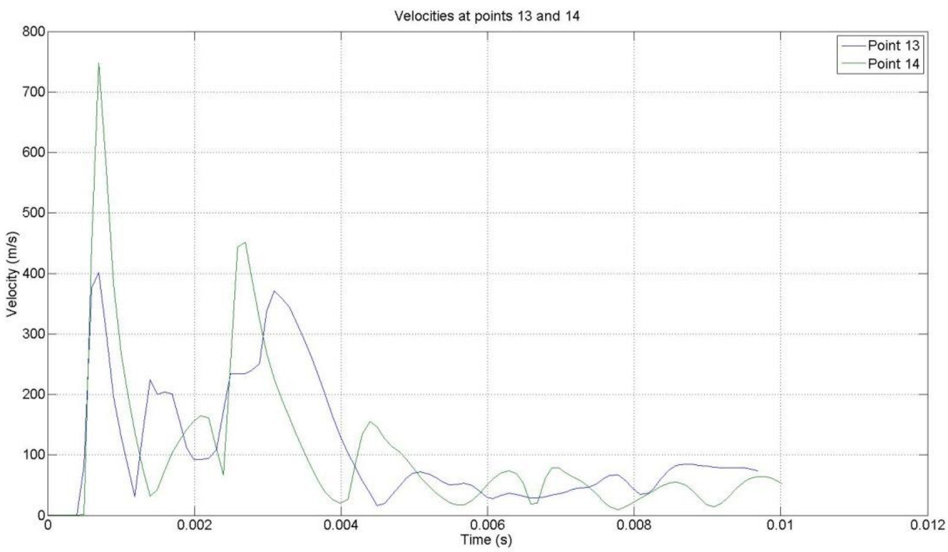

Fig. 19 – Resultant velocity at points 13 and 14. Model Case

At wall (point 14), the air arrives with a much higher velocity compared to air at the center of the bunker (point 13). Later, at both points the velocity is suddenly reduced to almost the same value in both cases. But since the velocity at wall was much higher, the kinetic energy that the fluid has to loose close to the wall is higher, which traduces to a higher increase of pressure at this zone. Everything originated by the existence of the wall boundary at this region.

From Fig.18 it is also interesting to note that close to the wall (Fig 18.b), there are much less secondary peaks compared to the region located on the center of the bunker (Fig. 18.a). The peaks secondary pressure peaks that are found on Fig. 18.a, that is, in the middle of the bunker are just reflections of the pressure originated at walls.

Despite of these reflections, once the main pressure front has passed this are the tendency of pressure is to recover its initial value, 0.1 MPa.

Now the second set of points is analyzed in Fig.20. This set studies a cross section of the principal hall of the bunker, but not so close to the explosion. Fig. 20.a shows the behavior on the center of the hall and Fig. 20.b the behavior close to the wall.

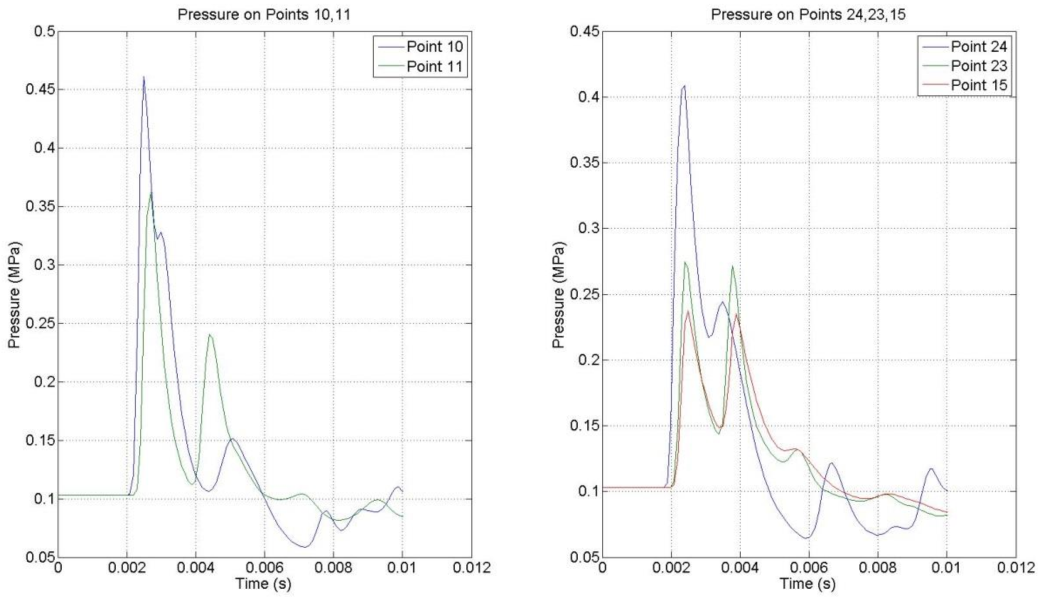

Fig. 20- Pressure Behavior at Points of Set 2. Model Case

In this case note that once we are not immediately close to the explosion point, the pressure peak that is produce either in the middle or in the wall is almost the same, but still higher close to the wall. Some reflection waves also appear behind the main one, but the most interesting thing to note in this plots, is the under pressure zone that occurs prior to stabilization of the pressure. This behavior is typical of free-air explosions. This zone, because it is more central receives several reflected waves from all directions. This fact traduces into a longer time needed for stabilization of the pressure.

The behavior of pressure on set 3 of points, that is, on the wall located just after the corner is shown in Fig. 21.

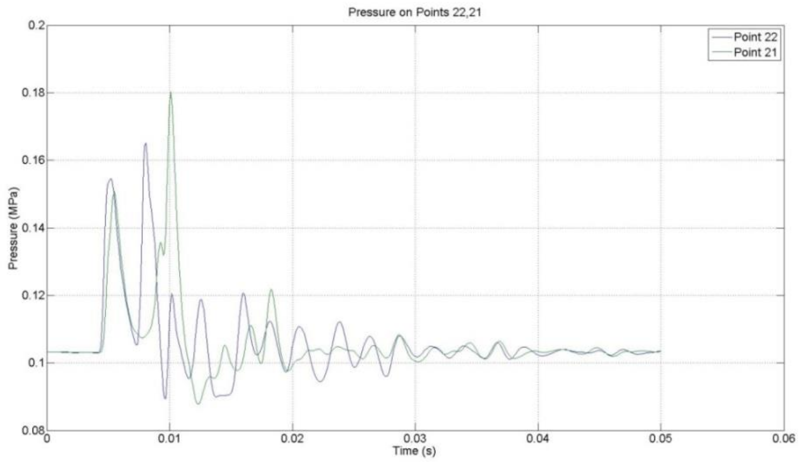

Fig. 21 – Pressure Behavior at Points of Set 3. Model Case

This region is surrounded by 2 walls, so the amount of reflected pressure waves is higher as it can be seen in the several pressure peaks on the plot that appears after the main pressure wave. This is due to the fact that the main pressure wave is "bouncing" between this wall and the end wall of the bunker, until it losses all the energy that the explosion provided to it. As a consequence of this, the pressure needs more than double the time to stabilize around initial value.

Fig. 22 comprises the behavior of pressure in the cross section right in between the previous studied wall (points 21 and 22) and the end wall (points from 1 to 9). It can be appreciated that the behavior, either close to the wall or close to the center is similar. This region is quite chaotic too, and once main wave have passed through it, several reflected waves will be crossing this zone. This can be appreciated again in the several pressure peaks on the graphs.

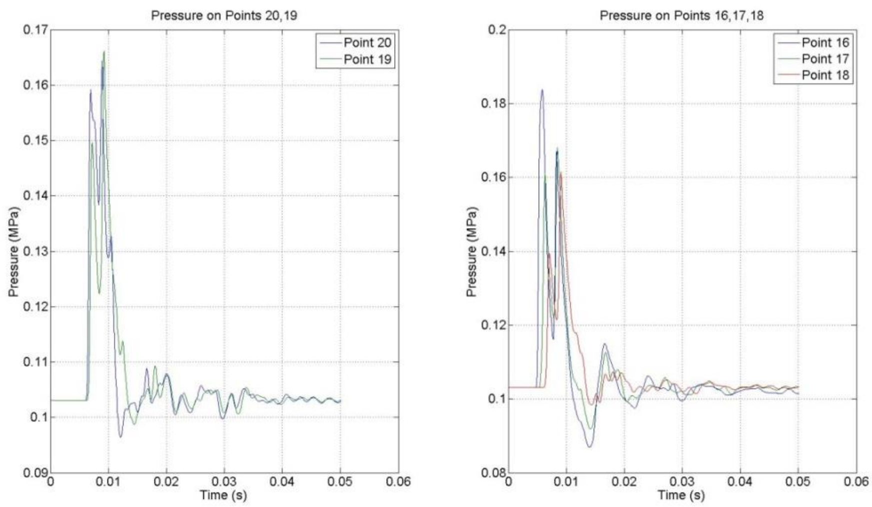

Fig. 22 – Pressure Behavior at Points of Set 4. Model Case

Another interesting conclusion then is to note that the release of energy through reflections is much less efficient than losing it by propagation, since in this cross section (points 16, 17 ,18 ,19 and 20) pressure needs around 50 ms seconds to stabilize. However, on the initial section (Points 12, 13, 14, 25, 26), where waves can propagate easier through the bunker, the time required for stabilization is just 8 ms seconds. Almost five times smaller stabilization time.

Finally, the pressure on end wall (Set 5 of points) is summarized in Fig. 23

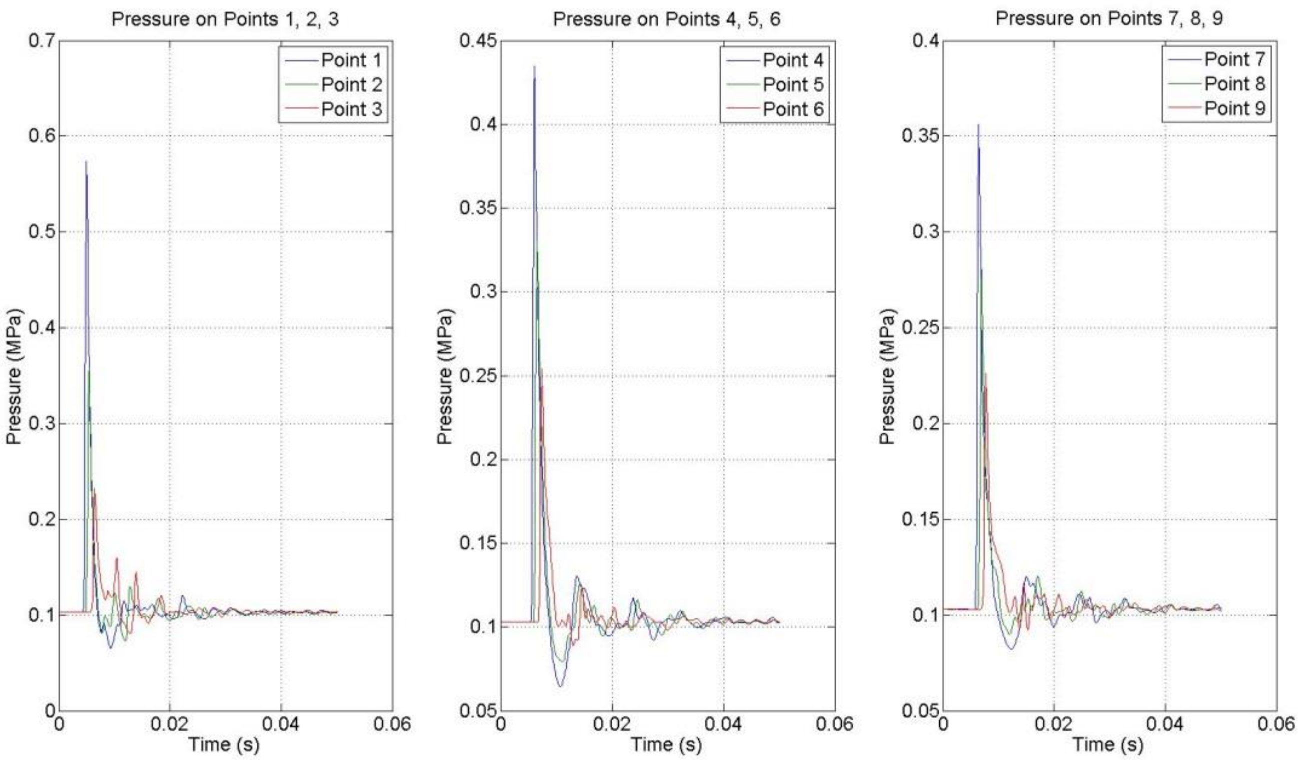

Fig. 23- Pressure Behavior at Points of Set 5. Model Case

Note that the pressure peak produced due the existence of the end frontal wall is one of the highest on the bunker,. Basically the entire main wave is reflected on this surface. Also note that this pressure peak is higher on the front surface of the step than on the wall itself. This is due to the smaller area this surface presents. As before, once main wave has impacted, a small under pressure zone is produced and then the reflected waves come into action until pressure stabilization is reached.

It is also remarkable that pressure peaks are lower as height is increased. Fig.23 shows clearly that pressure peak at points 1, 2 and 3 is higher than pressure peak at points 7, 8 and 9 located at a higher height. This behavior is repeated on all cross sections.

4.1.3 HEAD INJURY CRITERIA ANALYSIS

To have a better idea of the effects this blast will have on a human being, the Head Injury Criteria (HIC) will be analyzed. For a deep explanation and definition of this parameter, please refer to section 2.2. Just a brief reminder, this parameter studies the accelerations produced and the time interval in which they are produced.

Here below is possible to see a table summarizing the value of the HICS on the different points under study. To know the impact on a human being on each of the different points, pleaserefer to table 6.

HIC value over the different points of the bunker					
Point	HIC	Point	HIC	Point	HIC
1	29390	**10**	534300	**19**	10500
2	103400	**11**	278200	**20**	12230
3	81270	**12**	3179000	**21**	9310
4	32270	**13**	6337000	**22**	24690
5	63810	**14**	2637000	**23**	315400
6	70560	**15**	180000	**24**	332400
7	48610	**16**	49070	**25**	10640000
8	64690	**17**	24500	**26**	16630000
9	50170	**18**	9921		

Table 7- HIC values for model case at all points

According to table 6, there is no chance of surviving for a human being inside a bunker with this geometry. All regions present a HIC value above the surveillance threshold. However some interesting conclusions can be extracted.

In green, the points with the lower HIC value are marked. These points correspond to the upper part located just when turning the corner of bunker. That is, even if all points are critical for human life, this region represent the location where the effects of the blast are less severe.

4.2 VARYING EXPLOSIVE LOCATION ANALYSIS RESULTS

In this section, six different cases are going to be analyzed. Six cases in which the bunker geometry is kept constant and equal to the geometry defined on section 3.1, but the location of the initial explosion is changed. Fig. 24 summarizes the six locations where the explosive is going to be placed in each of the cases.

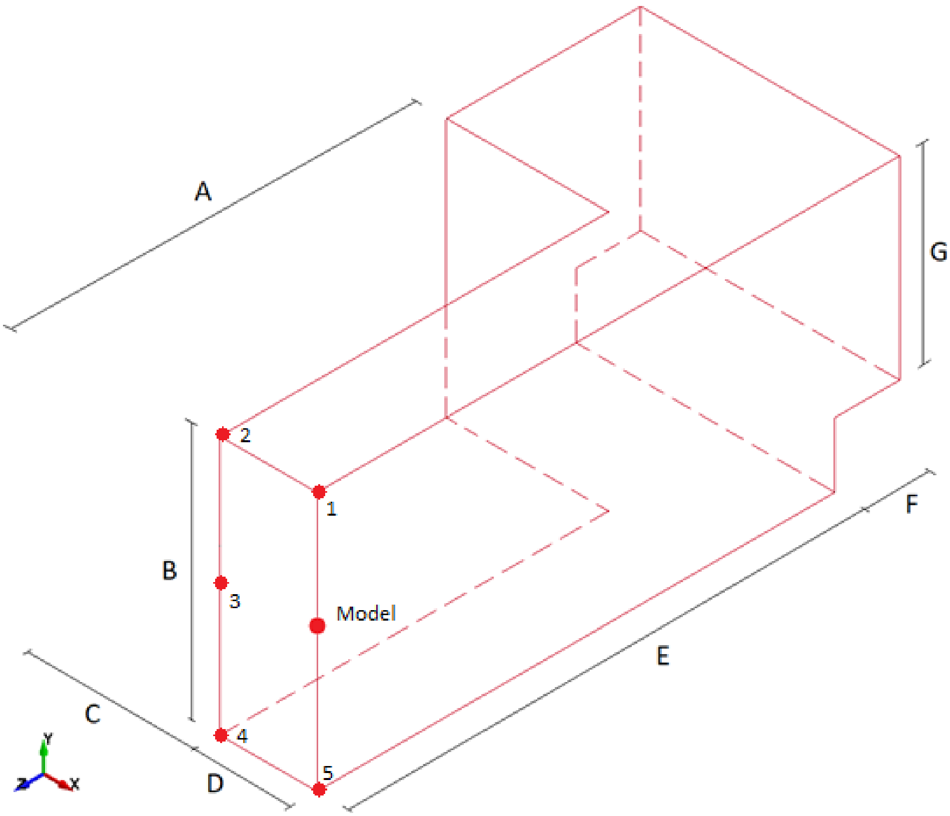

Fig. 24 - Explosive Locations Under Analysis

As in previous analysis, the first to study is the propagation of the pressure wave along the bunker for the six different explosive positions. Have in mind that all the figures used in this study have been taken at the same simulation time for each of the cases.

4.2.1 QUALITATIVE ANALYSIS OF PRESSURE PROPAGATION

Fig. 25 was introduced just to let the reader know in which position each case is going to be analyzed. These positions on following figures will be maintained for the whole analysis. From now on, just the number of each of the cases is going to be used to refer to it for the shake of simplicity.

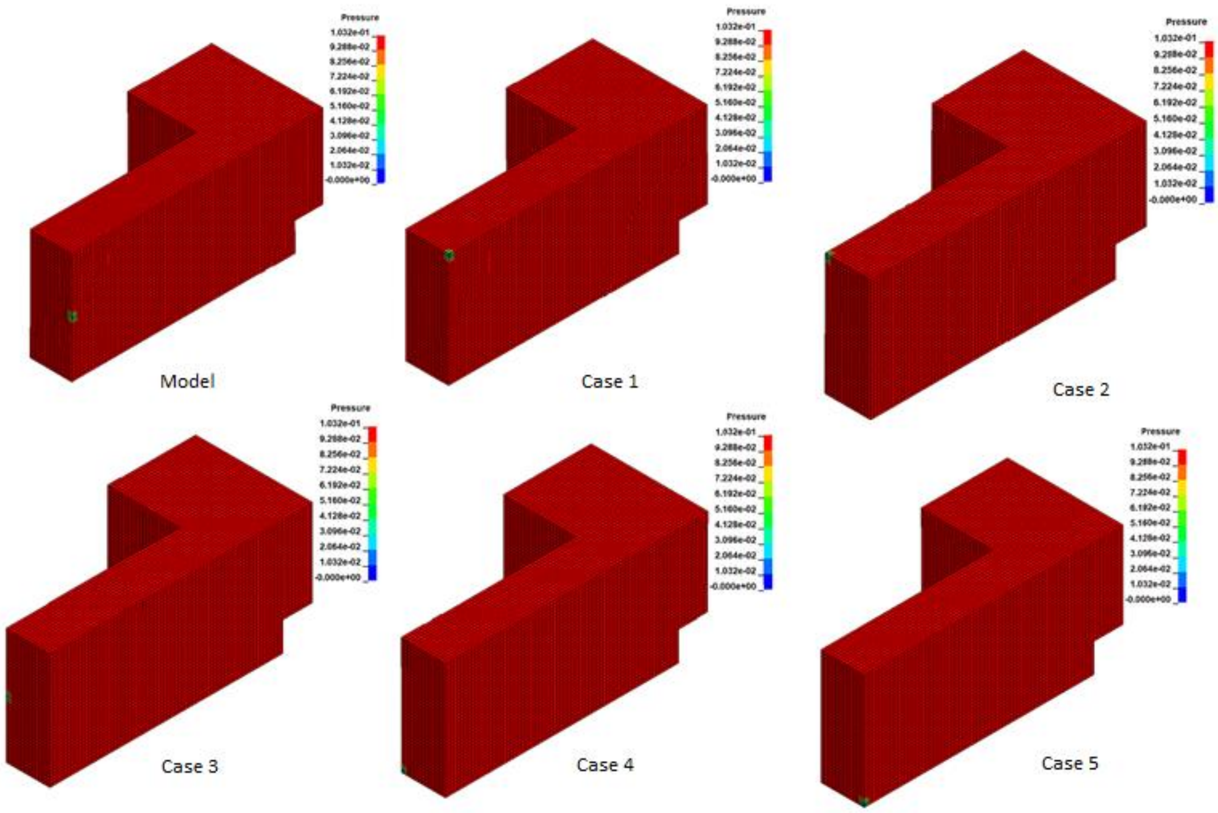

Fig. 25 – Explosive Location Pressure (MPa) Propagation. Step 1

It can be appreciated that geometry is the same in all cases, also initial pressure. The only thing changing as stated above is the explosive location.

In Fig. 26 it is possible to see how each of the pressure waves starts to propagate through the bunker. The most relevant fact that is perceptible as this point is that model and case 3, since the explosive was located at exactly half the height of the bunker, will propagate symmetrically.

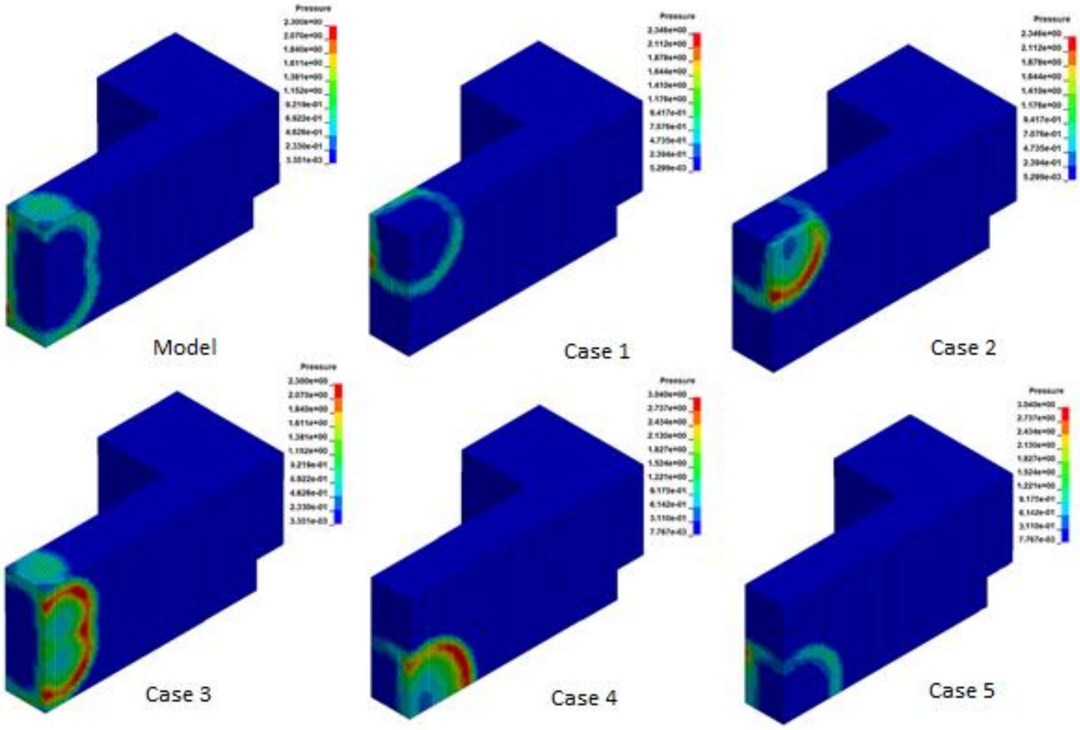

Fig. 26 – Explosive Location Pressure (MPa) Propagation. Step 2

Pressure waves propagate radially inside the bunker until they encounter a wall, but at this point, there is nothing more relevant to state. Pressure wave keeps propagating through the bunker main hall, and as expected reflected waves start to appear as can be appreciated in the pressure contours of the wall where the explosive where initially located. But yet it can be seen on Fig, 27 how radial propagation is still appreciable in all the cases.

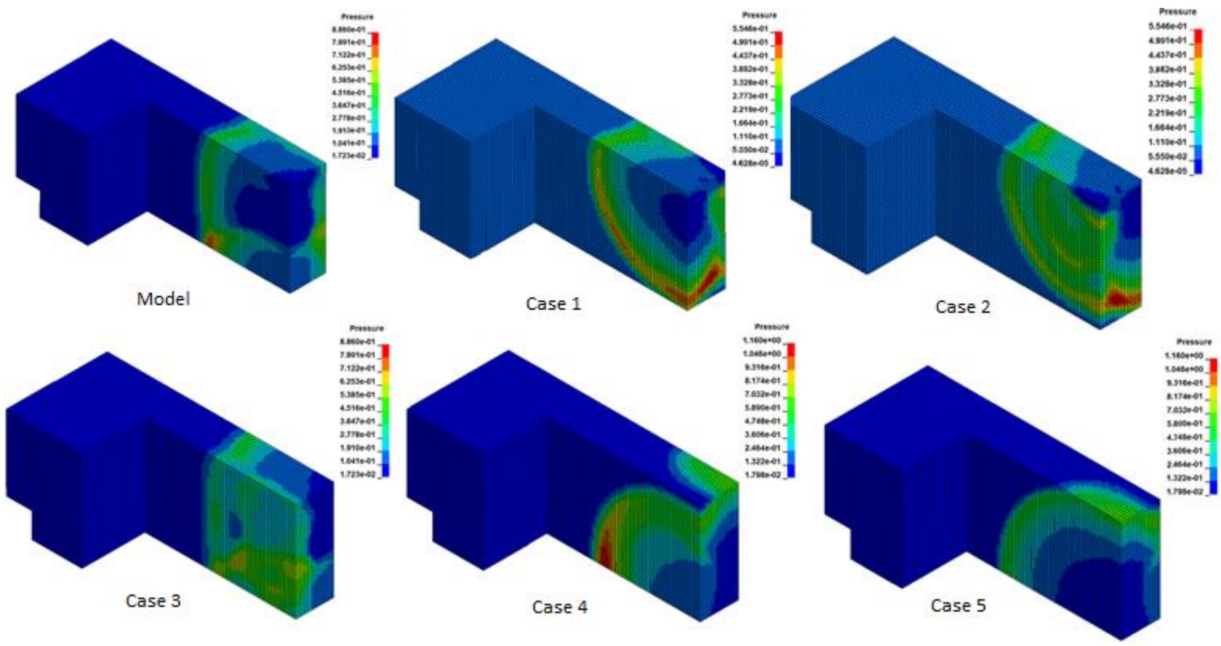

Fig. 27 – Explosive Location Pressure (MPa) Propagation. Step 3

The pressure front has moved more or less the same distance. However at this point, it is possible to start differentiating three different behaviors:

- Model case and Case 3 since their explosions happened exactly at half the height of the bunker have an homogenous constant profile of the pressure front from the floor to the roof.
- Case 1 and Case 2 since their explosions took place at the roof of the bunker, present a pressure front profile that has travelled more distance close to the roof than close to the wall.
- Case 4 and Case 5, had their explosions at the bunker floor so they present a pressure front profile that had travelled more distance close to the floor than close to the roof.

These three different behaviors are mainly the starting point of the different results that will be obtained during this section.

At this moment it is possible to see the main first difference in behavior, shown on Fig.28. When the same amount of time has passed, Model and Case 3 pressure fronts are just about to reach the bunker step. The pressure fronts of cases 1 and 2 have covered a smaller amount of distance, and there is still some unperturbed air between the pressure front and the step. Finally, pressure wave of cases 4 and 5 have already reached the step.

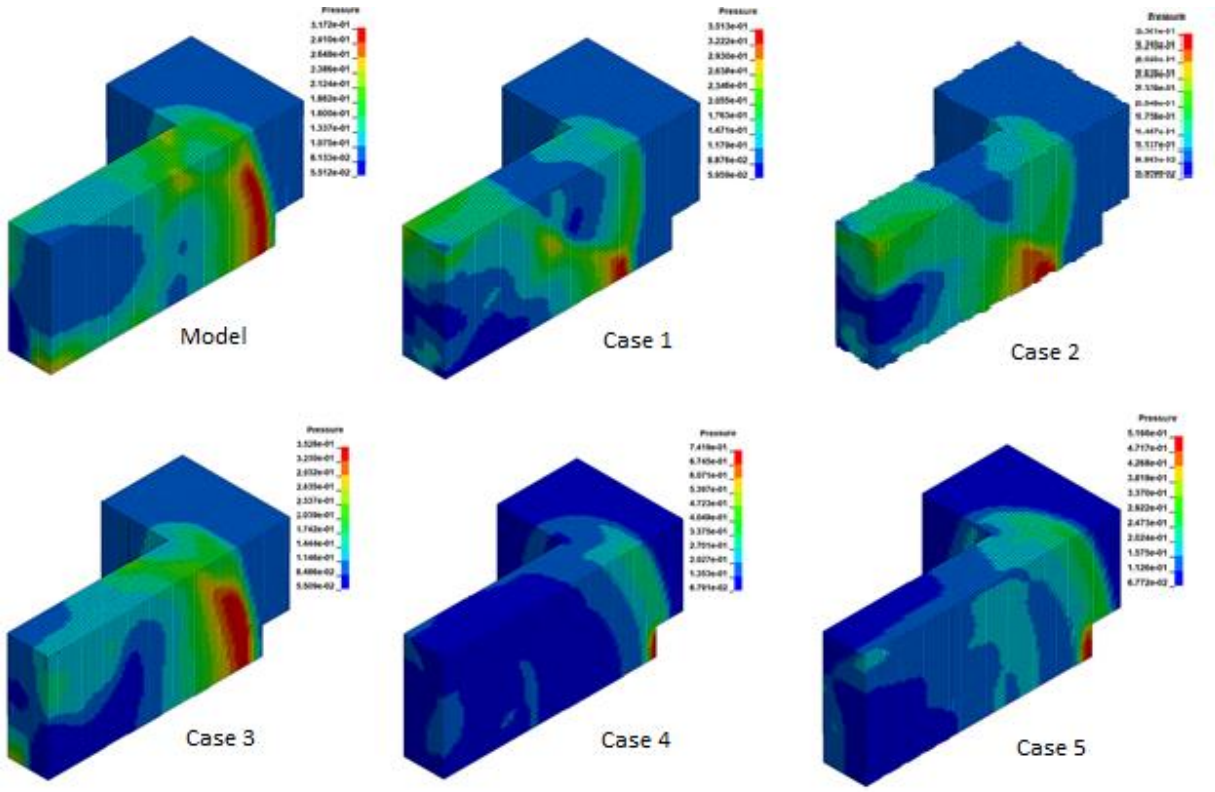

Fig. 28 – Explosive Location Pressure (MPa) Propagation. Step 4

All this phenomena is due to what it is explained in Fig.28 mainly to the geometry of the pressure front.

Fig. 29 and Fig. 30 show exactly the same results. When Model and Case 3 pressure fronts reaches the end wall of the bunker, pressure front of cases 1 and 2 are slightly behind, still reaching the step, and the ones from case 4 and 5 slightly after, the pressure front has reached the end wall of the bunker and it is starting to propagate laterally.

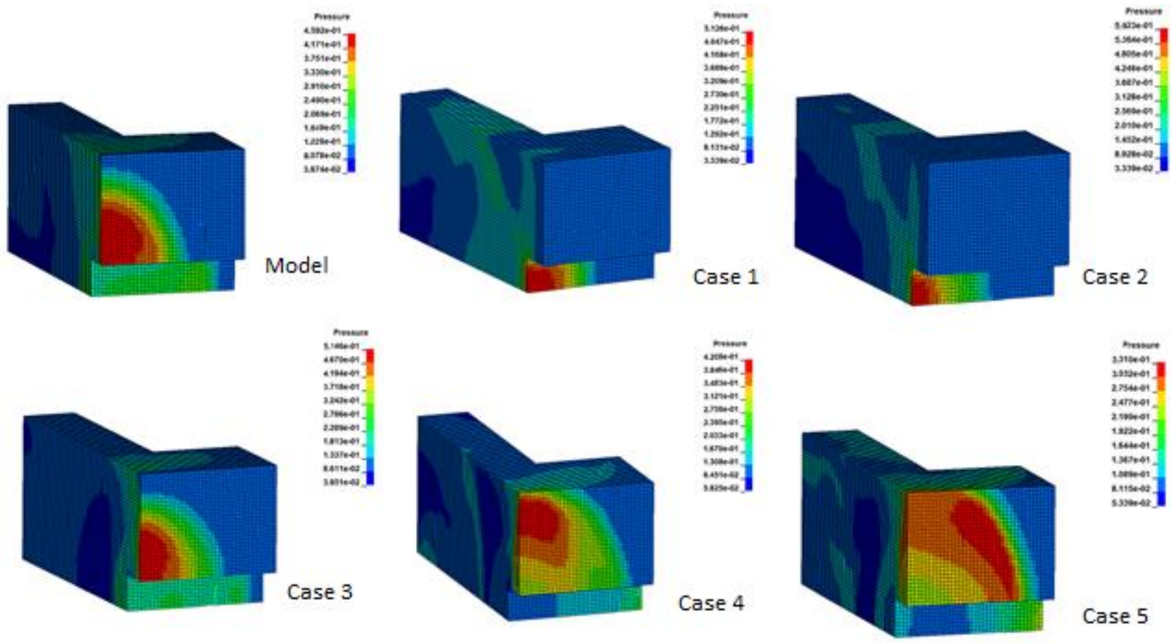

Fig. 29- Explosive Location Pressure (MPa) Propagation. Step 5

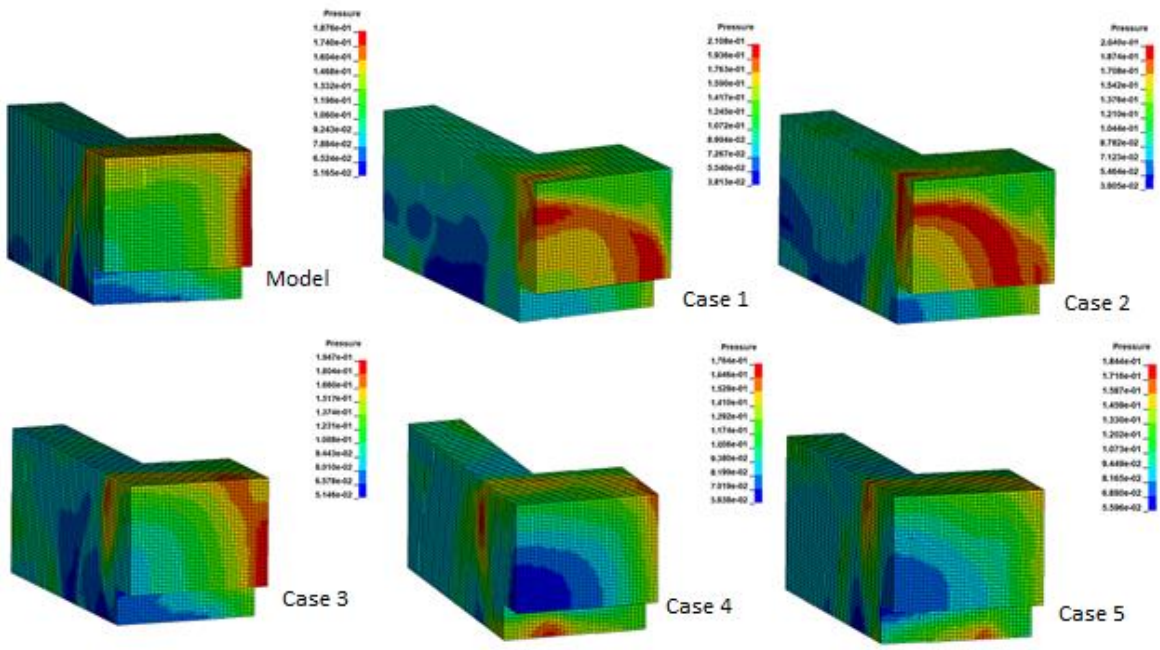

Fig. 30 – Explosive Location Pressure (MPa) Propagation. Step 6

After these images, pressure waves bounce back and forward until pressure stabilization is reached in the bunker. This happens for the six different cases.

So basically, without changing the geometry of the bunker it seems reasonable to expect similar behavior of the pressure regardless of the position of the initial explosion. However, by varying this position some advancement or retardation of the effects shall be expected.

At this point, it may also be interesting to look at the pressure values to see if there are any remarkable differences, despite of the similar behaviors.

4.2.2 QUANTITATIVE ANALYSIS OF PRESSURE

As in section 4.1.2, the pressure is going to be studied on different points. From those close to the explosion point to that ones located further and where the pressure waves arrive later.

The distribution of these points is the same as that of section 4.1.2. However it is shown here again in order to refresh it.

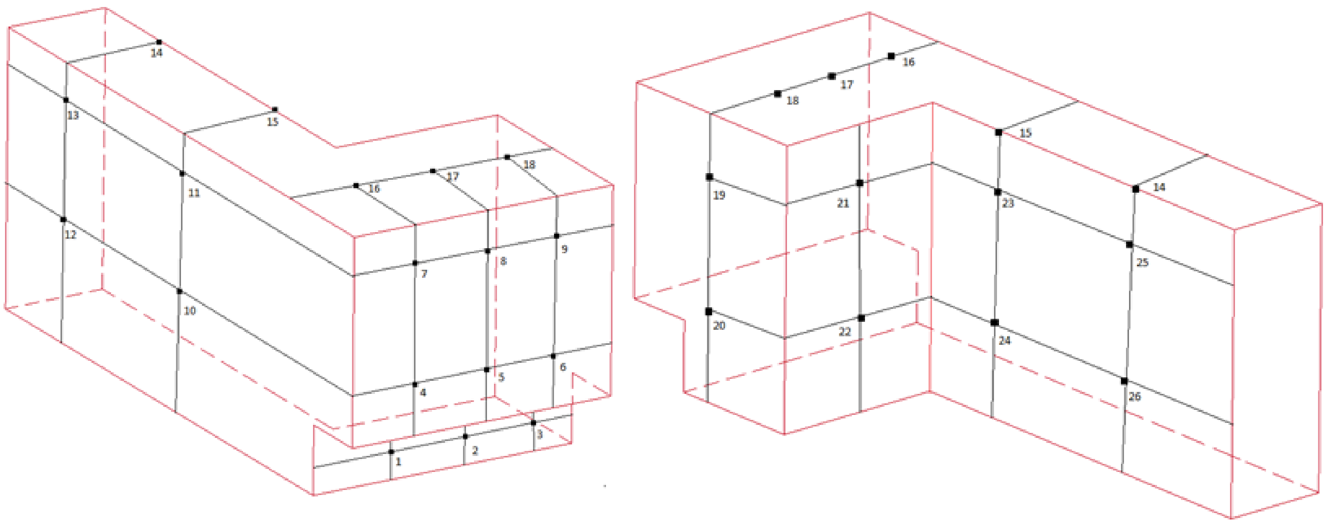

Fig. 31 – Distribution of points under analysis

Set Number	Points inside the set
1	12, 13, 14, 25 ,26
2	10, 11, 15, 23, 24
3	21, 22
4	16, 17, 18, 19, 20
5	1, 2, 3, 4, 5, 6, 7, 8, 9

Table 8 – Sets of Points Under Study

Fig. 32 corresponds to the cross section closest to the explosion point. For each case, the zone with higher pressure value is reached on the opposite side of the explosion. That is why, for instance, in point 25 (located upwards to the right) shows a particularly high pressure peak corresponding to Case 1 (explosive located upwards in the center of the bunker)

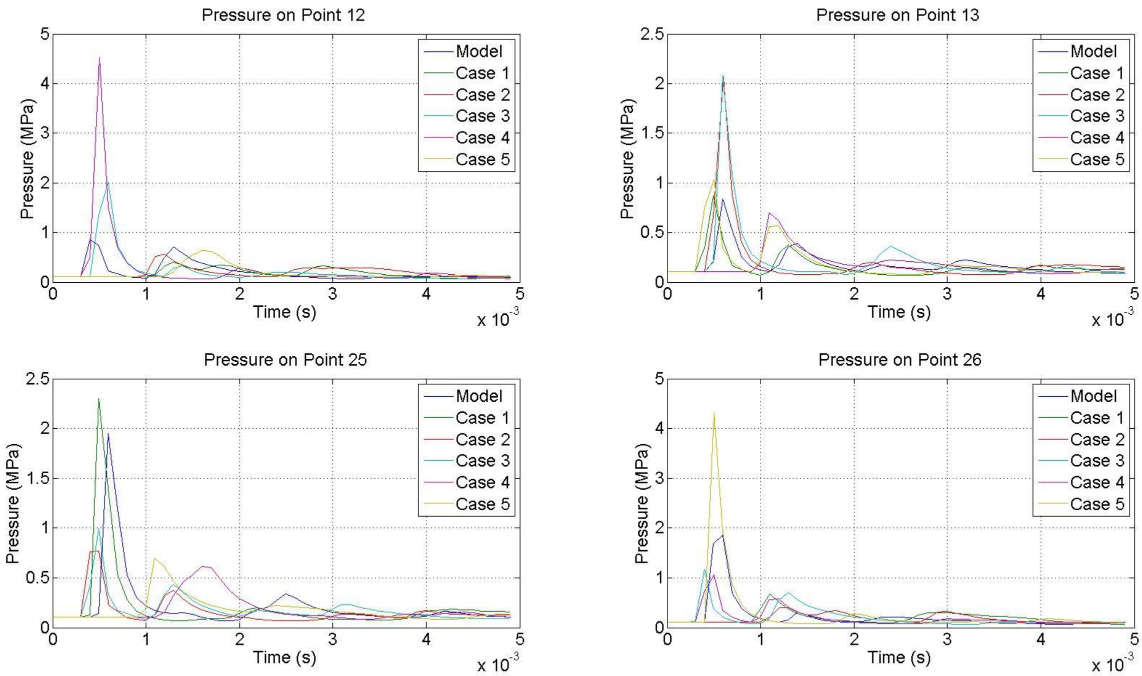

Fig. 32 – Pressure Behavior at Points of Set 1. Explosive Location Case.

A part from this characteristic behavior, it is only worthy to mention that secondary waves behavior is not very intense on this points. It seems like once the main pressure wave has passed, the pressure tends to go to its initial value relatively fast and without big disturbances.

For the next cross section, shown in Fig.33, now a little further from the explosion it can be seen that the behavior of all cases is more homogenous than before. One thing interesting to mention is the slightly higher pressure peak corresponding to case 5 that it is possible to see on points 10 and 11. Also the higher pressure peak corresponding to case 4 on points 23 and 24.

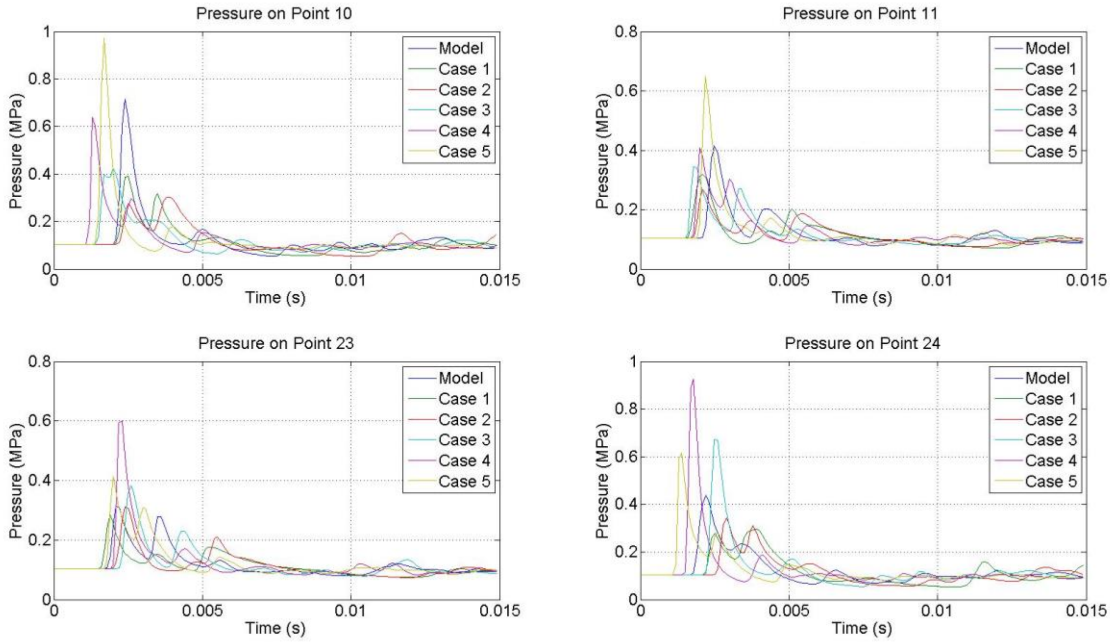

Fig. 33 –Pressure Behavior at Points of Set 2. Explosive Location Case

In both cases the behavior is similar since the higher pressure peak corresponds to the case where the explosive location was in the same side as the points but downwards. This fact must just be due to reflections and this particular geometry. A part from that , the behavior of all cases is similar, depending on the case, the pressure front arrives earlier or later to the different points, and as in previous cross section, once the main wave have passed the behavior of the pressure tends to recover its initial value without major disturbances or secondary waves.

In Fig. 34, it can be confirmed the statement exposed on previous section. This statement was that the location of the explosion will generate different profiles of the pressure front. These different profiles will have as consequence that the main wave of different cases arrives earlier or later to different points.

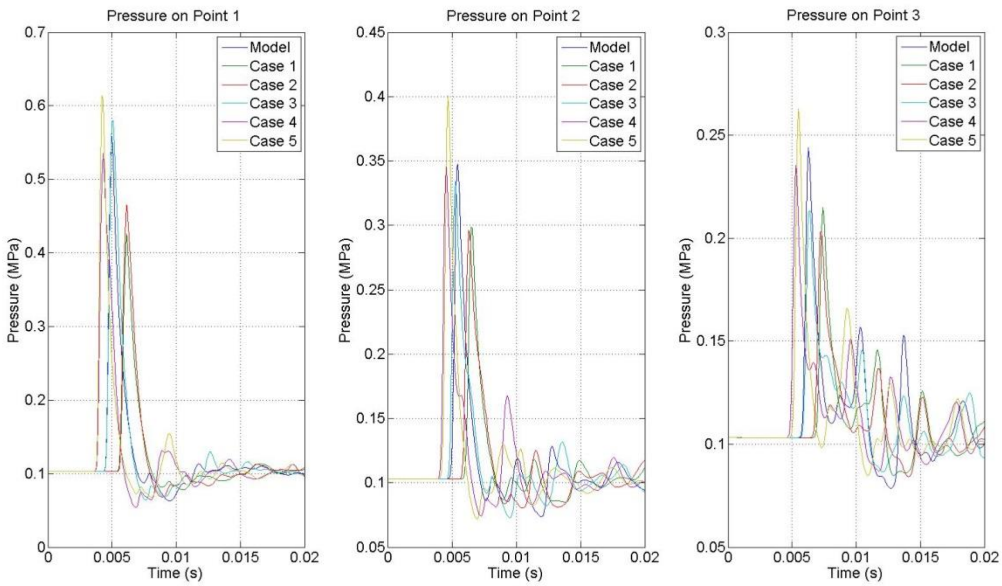

Fig. 34 – Pressure Behavior at Points 1, 2 and 3. Explosive Location Case

For this particular case, note that points 1, 2 and 3 are located at the end of the bunker. The first waves arriving to these points are those for the cases 4 and 5, that is, the cases where explosion occurs close to the floor. As seen before on Fig.27, the developed pressure profile covers earlier the bunker main hall and reaches the bunker ramification.

Then, the second waves arriving are those of model and case 3, where explosions take place at half the height of the bunker. This explosion creates a pressure profile that is homogeneous along the whole height of the bunker (Fig.27) due to symmetry.

Finally cases 1 and 2, where explosion occurs on the upper part of the bunker are the last arriving to these points.

The difference in the pressure magnitude can also be explained again by the position of the explosion. It seems reasonable, and it is also show in pressure front profile figures, that the cases where explosion occurs close to floor show higher pressure values due to the existence of the floor, that reflects the wave increasing its pressure and velocity, and as the initial explosion location moves away from the floor the value of the pressure front decreases.

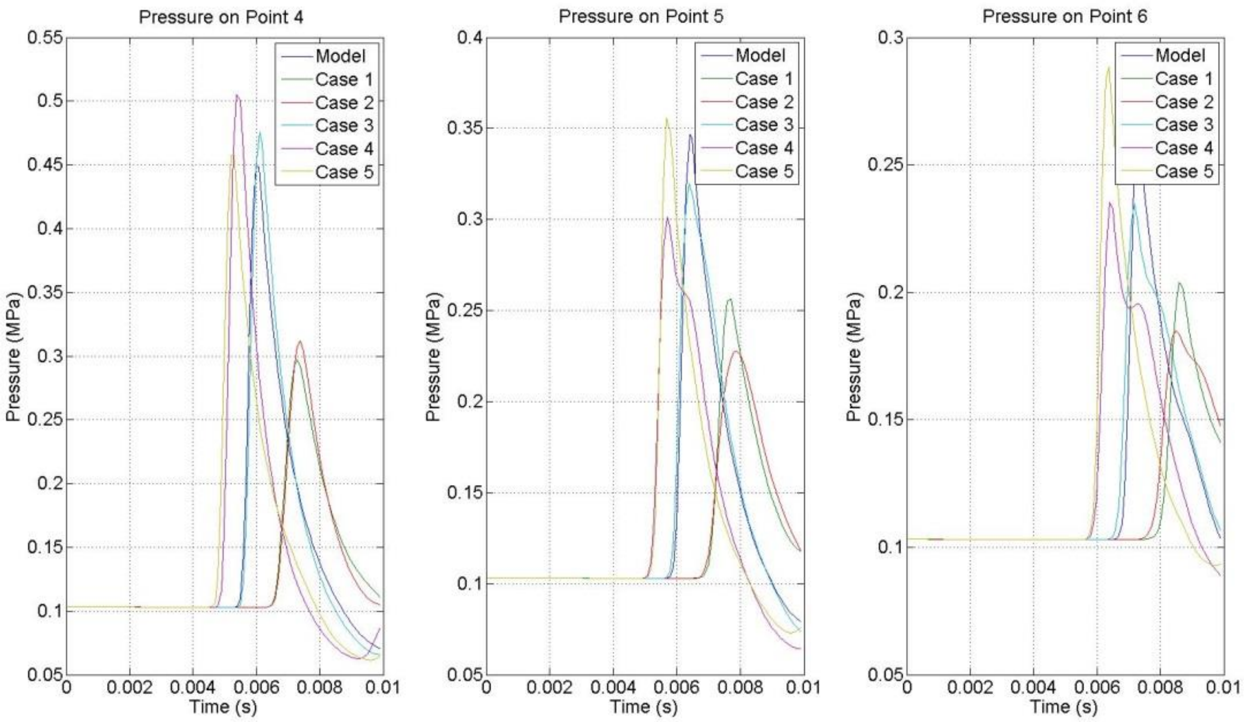

Fig. 35– Pressure Behavior at Points 4, 5 and 6. Explosive Location Case

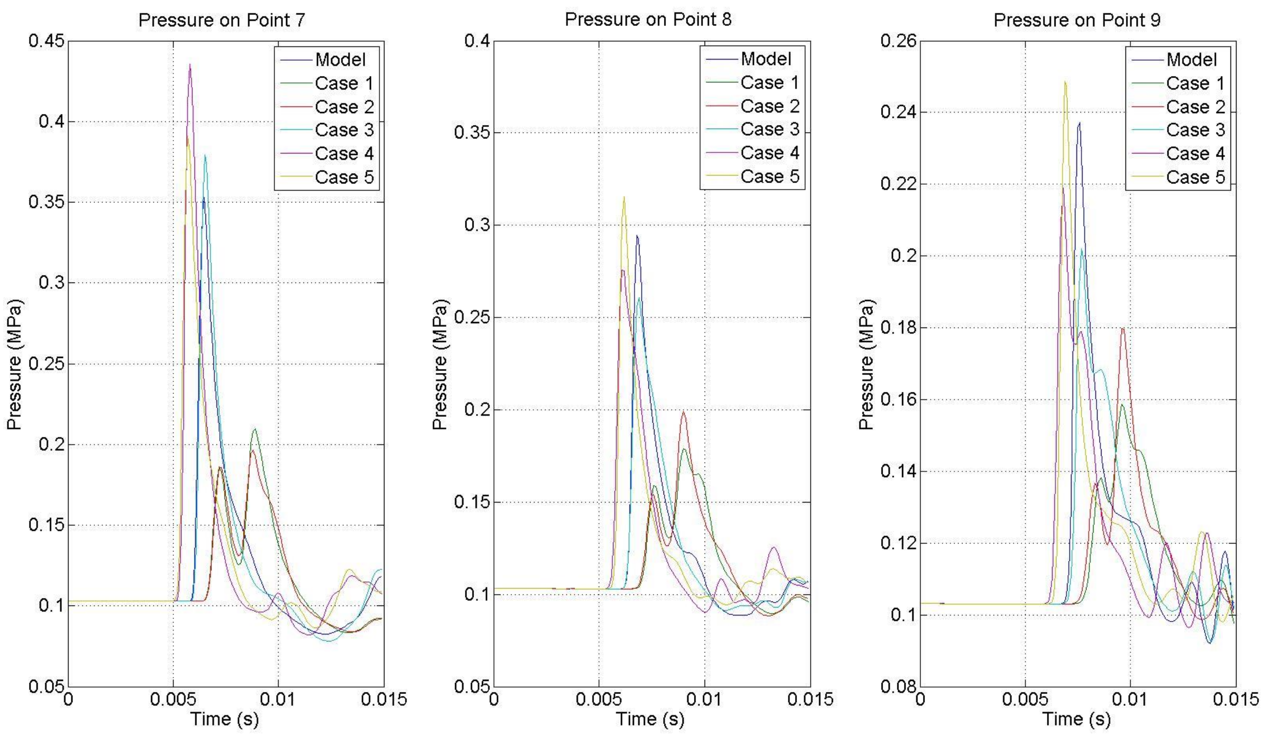

Fig. 36 – Pressure Behavior at Points 7, 8 and 9. Explosive Location Case

In Fig. 35 and Fig. 36 images, it may be thought that the behavior should be the same as before. That is since points 4, 5 and 6 are located at half the height of the bunker, the first waves arriving to this points should be the ones from model and case 3 since its explosion occurs at the middle height of the bunker. In the same way, at points 7, 8 and 9 (located at the roof of the bunker) one may think that the ones arriving first are those corresponding to cases 1 and 2, since it explosion occurs at the bunker roof.

However, in all cases it is seen that the behavior is not like this. The firsts wave arriving are always the ones corresponding to cases 4 and 5, where the explosion took place at the floor of the bunker. As said before the existence of a floor, creates a reflected wave of higher pressure and velocity. Also as the wave travels through the bunker hall, the profile became more homogenous (especially as we approach the lateral ramification) as it can be seen in Fig. 37.

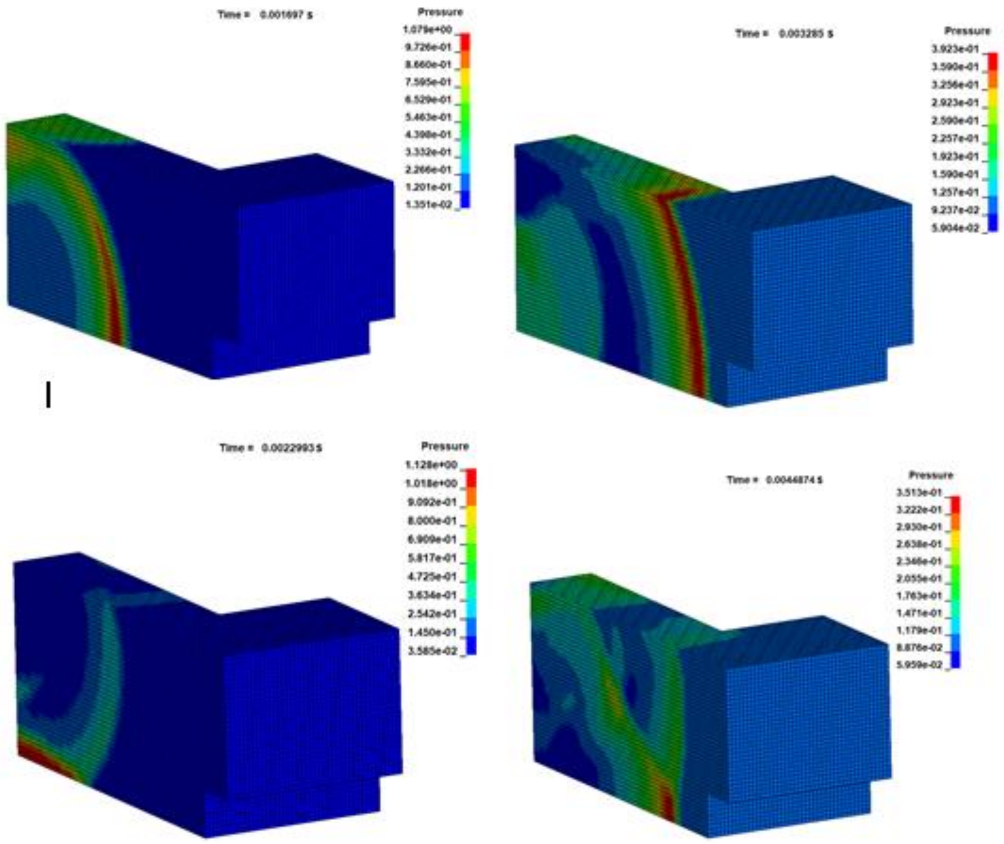

Fig. 37- Evolution of the pressure (MPa) front along the bunker hall

4.2.3 HEAD INJURY CRITERIA ANALYSIS

At this point, Head Injury Criteria (HIC) is going to be analyzed for the different cases in order to see if there is any particular location where the effects of the explosion on a human been are less severe.

Unfortunately, there is no location where survival is possible (HIC<1860), however as in the previous section, this data can be used to get some conclusions.

First of all state, that close to the explosion location the HIC value is so high that no graphical data is going to be included. The interesting facts occurs at locations close to the end of the bunker.

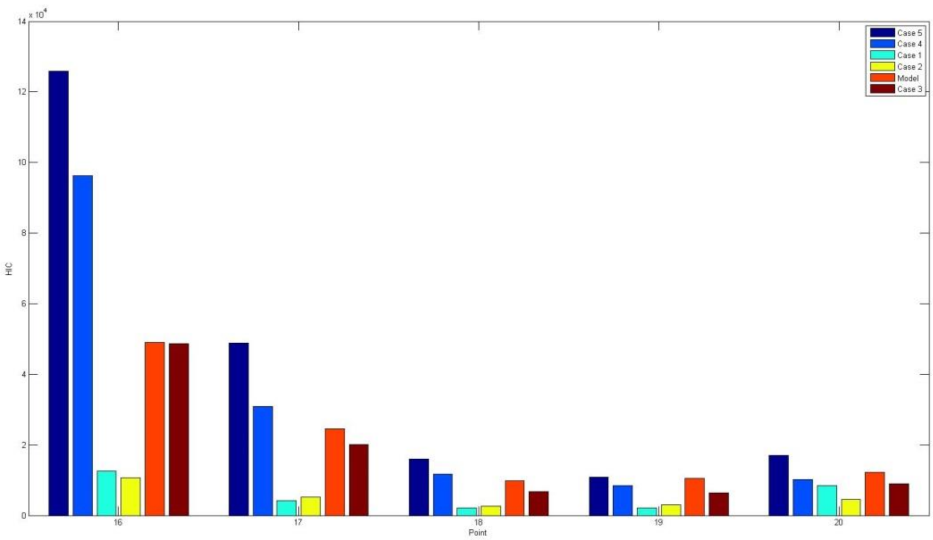

Fig 38 – HIC value at points 16, 17, 18 ,19 and 20. Explosive Location Case

For positions close to the end of the bunker (Points 16, 17, 18, 19 and 20) even if all cases are mortal for human, it can be appreciated that the mortality of the explosion decreases as we move towards the bunker ramification. Point 16, which is just in front of the explosion shows a much higher value of HIC than point 18, which is inside the ramification of the bunker.

Another interesting result that is appreciable is that cases 1 and 2, where explosive was located upwards shows a significant decrease in mortality compared to cases 4 and 5, where explosive was located at the floor. This fact has been deeply explained on Section 4.2.2

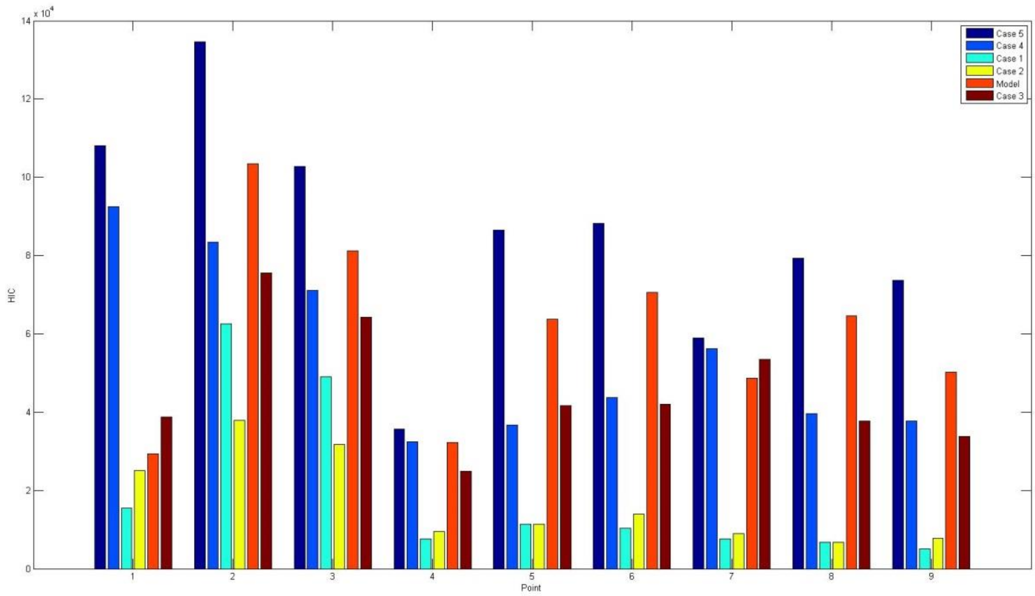

Fig. 39 – HIC values at points 1, ,2, 3, 4, 5, 6, 7, 8, 9. Explosive Location Case

This last figure shows the HIC value for all cases at the end wall. As it can be seen the behavior is quite similar as in the previous image. Cases with explosive above have much less criticality than the other cases. So the higher the explosion occurs on the bunker, the more chances have humans to survive to it, for this particular case. In general words, the further to a wall the explosion occurs, the higher chances of surviving since no reflections appear.

4.3 VARYING GEOMETRY ANALYSIS RESULTS

In this section, the explosive will be kept in the middle of the bunker, at the red point of Fig. 40, for all cases. But the geometry will be varied in order to appreciate the influence of the geometry on the explosion. Geometry changes will be applied to what will be called from now on "Main Hall". Being this section the prism formed by sides B-D-E of Fig. 40.

The different dimensions of the six cases under study are summarized in Table 8.

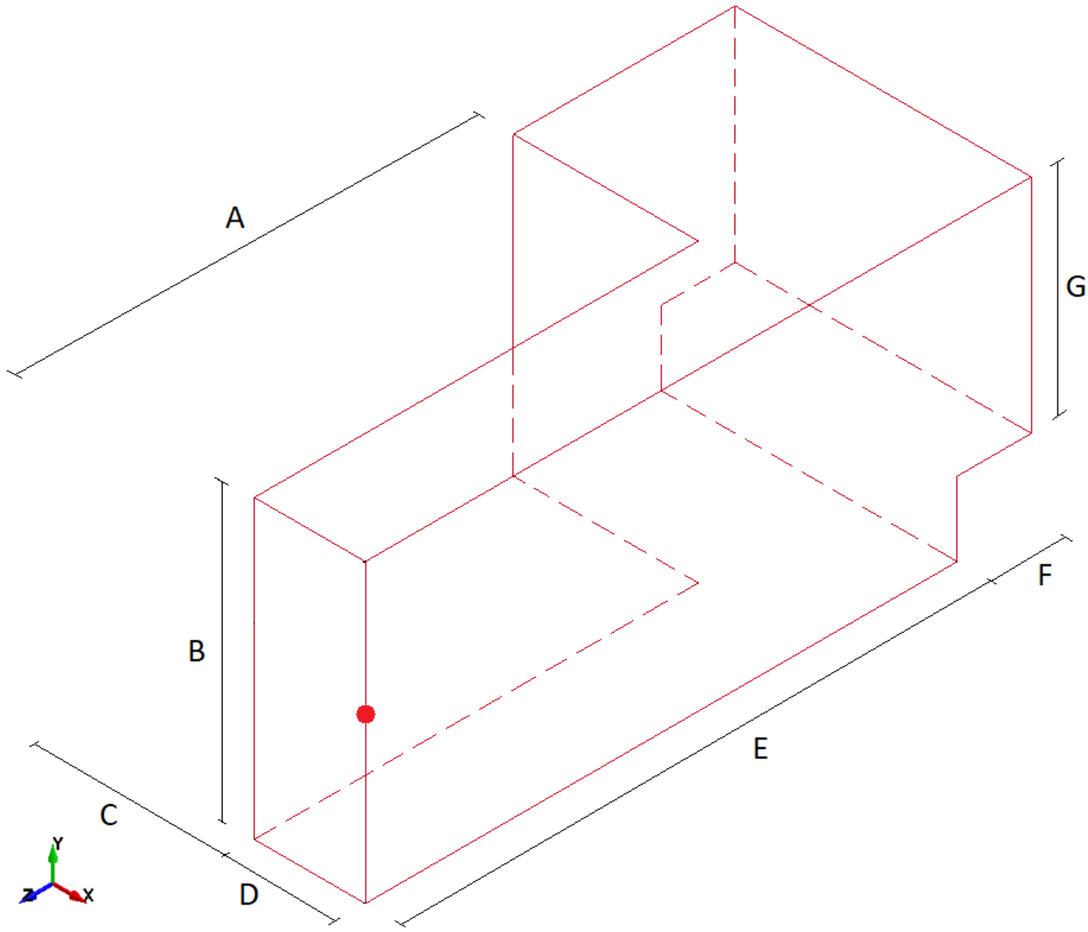

Fig. 40 – Geometries of the Bunker

Case:	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]
Model	3000	2000	1250	750	4000	500	1500
1-High Hall	3000	3000	1250	750	4000	500	2500
2-Low Hall	3000	1000	1250	750	4000	500	500
3-Long Hall	4500	2000	1250	750	5500	500	1500
4-Short Hall	1500	2000	1250	750	2500	500	1500
5-Thick Hall	3000	2000	1250	1500	4000	500	1500
6-Thin Hall	3000	2000	1250	300	4000	500	1500

Table 9 – Dimensions of the Cases under study

4.3.1 QUALITATIVE ANALYSIS OF PRESSURE PROPAGATION

Fig. 41 is basically introductory. It can be seen that the explosive is always initially located at the middle of the front face of the bunker. Also, the different geometries can be appreciated.

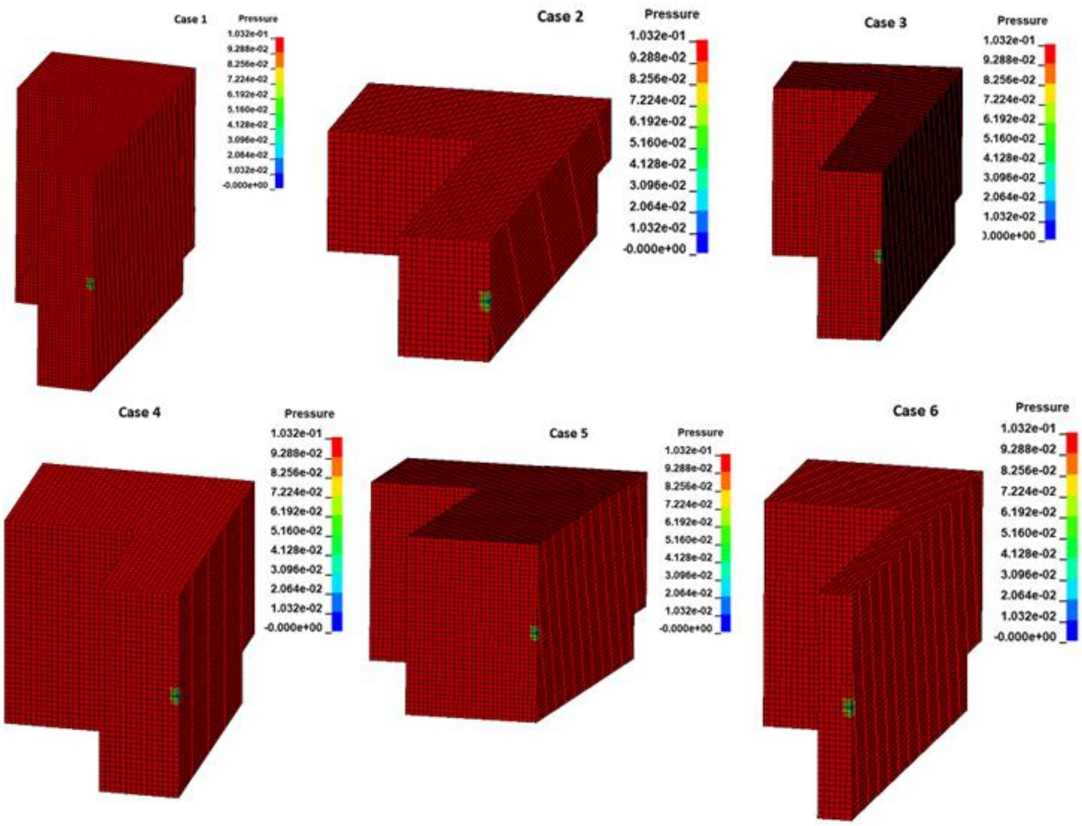

Fig. 41 – Varying Geometries Pressure (MPa) Propagation. Step 1

The different geometries come into pairs, in order to check respect the original geometry what changes appears in one direction or the opposite. In this way, Cases 1 and 2 vary the height of the main hall respect the original one, being Case 1 higher and Case 2 lower. In a similar way cases 3 and 4 vary the longitude of the main hall, being case 3 longer and case 4 shorter. Finally cases 5 and 6 vary the width of the main hall, where case 5 is thicker and case 6 is thinner. In the next pages the changes originated in pressure propagation and HICs due to these varying geometries will be analyzed.

It is also very important to mention, that the following sets of images where taken at the exact same time, in order to have an adequate analysis of the differences in pressure propagation between cases.

In Fig. 42, a similar behavior in all the cases can be appreciated. Explosion occurs and pressure starts to propagate radially through the bunker until it encounters any wall.

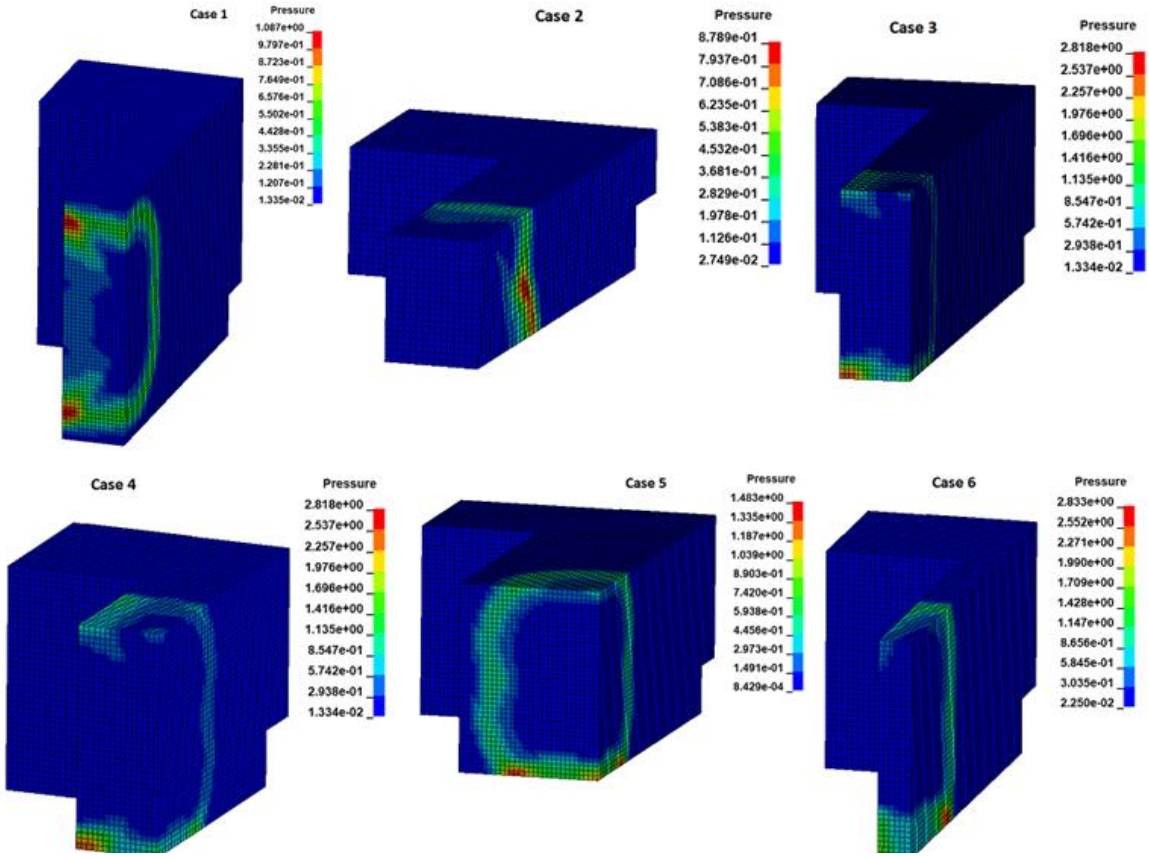

Fig. 42 – Varying Geometries Pressure (MPa) Propagation. Step 2

When a wall is found, pressure suffer an increase in value and starts to propagate parallel to that wall instead of radially, as it has been seen and explained in section 4.1 and section 4.2.

At this point, a slightly different behavior can be seen. In cases where the volume of the bunker has been reduced in any way (cases 2, 4, and 6) the pressure front has been able to propagate deeper in the bunker. This fact totally makes sense, since the radial propagation step lasts less time in these cases because a wall will be encountered earlier.

However, these differences are not significant at the moment, but it will be shown that later in the explosion process this fact will have some influence on the behavior of the pressure waves of each of the cases.

In Fig. 43 this behavior can be already confirmed. Cases 2, 4 and 6 have already its main pressure wave well defined and approaching the step of the end wall. While in the other cases, pressure front is barely created and has not propagated not even to the half of the main bunker hall.

Another important point to start noticing at this moment is the behavior of the main pressure wave of case 2 (Low main hall). In the other five cases it can be seen that the pressure front presents a gradient in the direction of the height, being stronger close to the floor of the hall, and weaker at the roof.

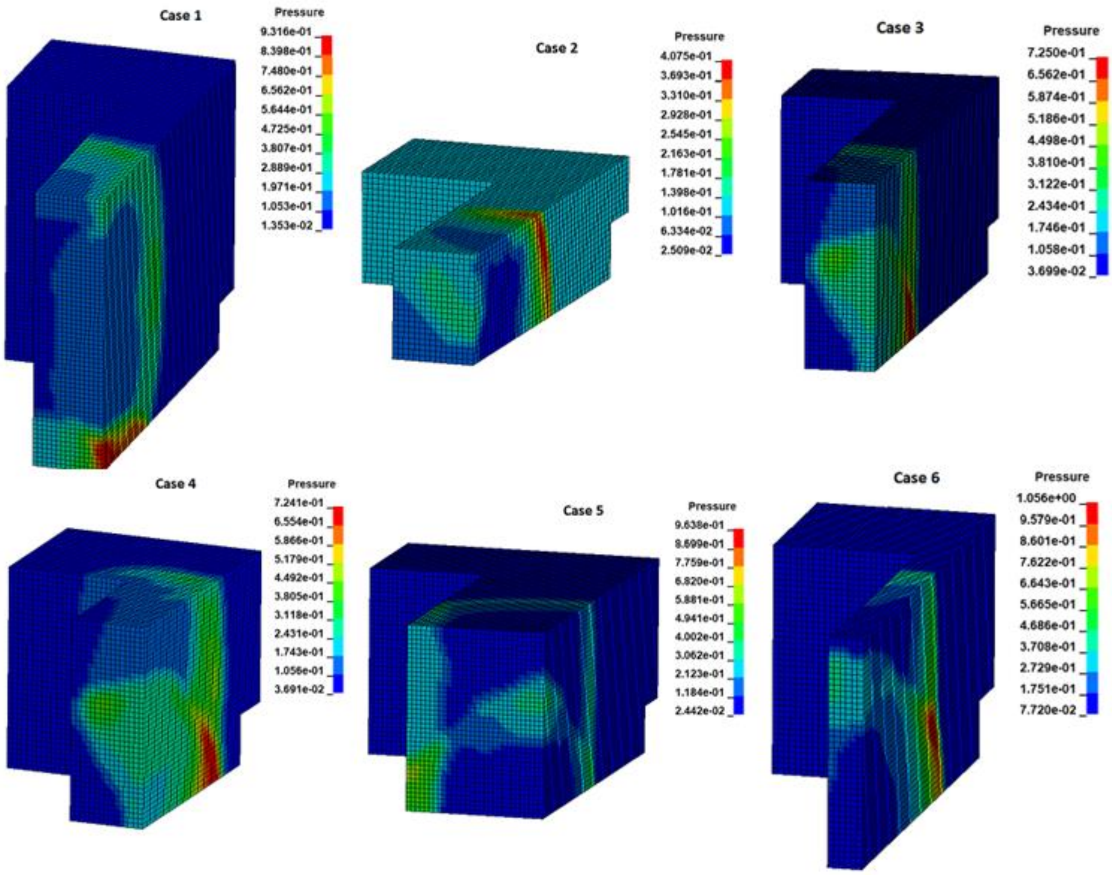

Fig. 43 –Varying Geometries Pressure (MPa) Propagation. Step 3

However the particular geometry of case 2 has a remarkable consequence, at this moment an homogeneous and strong pressure front can be appreciated. This front does not present the clearly defined gradient that it can be seen in the other cases. For case 2, the pressure front presents almost the same strong value from floor to roof. This fact will have severe effects later, as it will be shown.

Later on the explosion, in Fig. 44 in most of the cases the pressure front keeps developing and travelling towards the end of wall. Some particular behaviors can be seen however.

It is mainly remarkable how for case 2 a strong pressure peak appears at the location of the explosion. The appearance of this peak is due to the interaction between main pressure wave and the reflected ones. Note that for case 2, floor and lateral walls are very close to each other compared to other cases, so reflections will be intense.

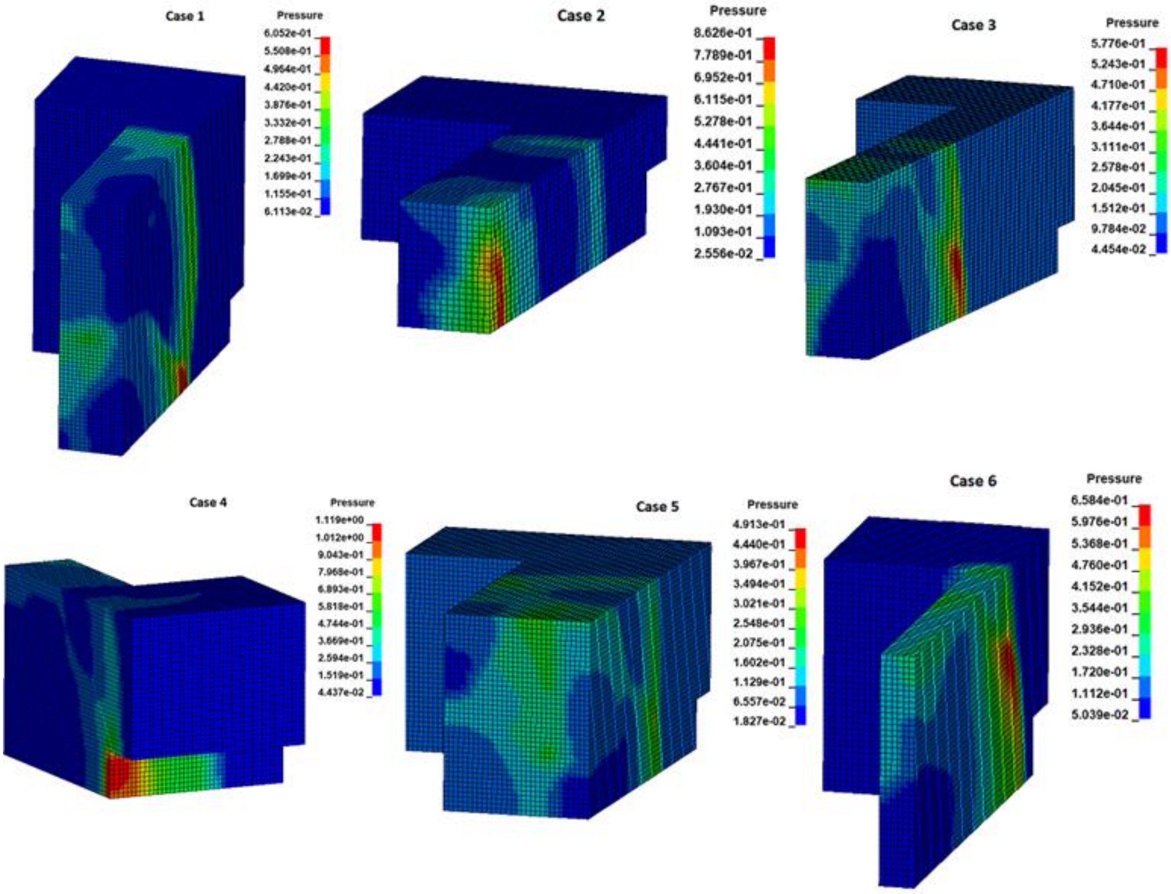

Fig. 44 – Varying Geometry Pressure (MPa) Propagation. Step 4

For case 4, which is the one with the shortest hall, the pressure front has already reached the step of the end wall. The combination of a reduced volume and reducing it through the hall length ends up in a pressure front reaching the step much faster than the other cases. On the other hand, for case 5, which is the one with the biggest volume compared to the rest of the cases, the pressure front has not even completely developed yet. It is the opposite effect. Pressure front needs more time to cover all the volume. Having the lateral walls more separated ends up in having a smoother distribution of the pressure.

At Fig. 45, all pressure fronts have reached the end wall step or are just about to do it. Cases with smaller bunker volume (cases 4 and 6) have already reached the end wall, the pressure front has collided against it and it is now propagating laterally.

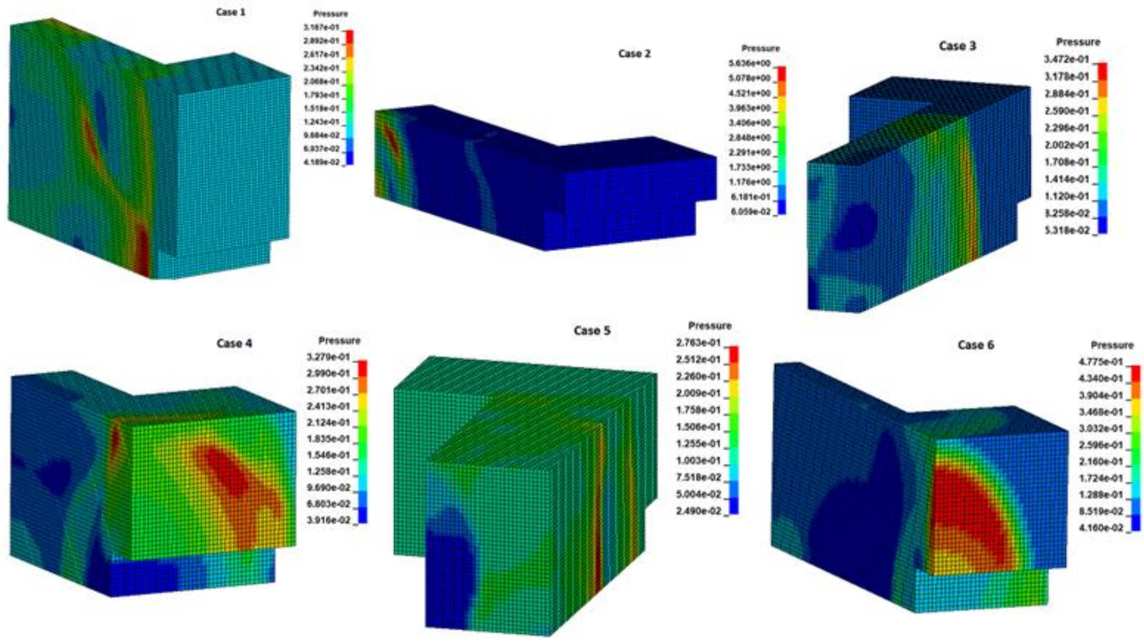

Fig. 45 – Varying Geometries Pressure (MPa) Propagation. Step 5

There are two particular behaviors, those of case 2 and case 5. They will be analyzed separately.

For case 5, even if the pressure front has not reached yet the end wall step, due to the higher volume and space the pressure has to propagate, the pressure inside the bunker has become almost the same in all the zones. This behavior has not been observed in any of the previous cases. The normal behavior has been a high value pressure front (of the order of 10^-1 MPa) traveling and leaving behind a zone of lower pressures (of the order 10^-2).

However, by increasing the width of the main bunker hall it has been reached a situation in which both the pressure front and the pressure zone left behind are of the same order of magnitude (10^-1 Mpa). That means that the pressure differences across the bunker will not be so high and therefore air accelerations will be lower. This fact will translate into having smaller Head Injury Criteria in this case, as it will be seen later on section 4.3.3.

For case 2, lower height wall, the behavior is completely different. First of all it is very important to not only analyze it by the colors, since at this particular point they may confuse more than they help. The fact that that almost all the bunker is in blue, does not mean that the pressure is low in there. In fact, the blue pressure value of case 2 is higher than most of the red pressure values of other cases. However, pressure values will be better explained further on section 4.3.2, using more appropriated graphs. At this point is enough to keep in mind that pressures of case 2 are the highest ones of all the cases under analysis.

Again respect case 2, as it can be seen in Fig. 46, the creation of the high pressure zone close the initial explosion location has created retardation in the propagation of the main pressure wave.

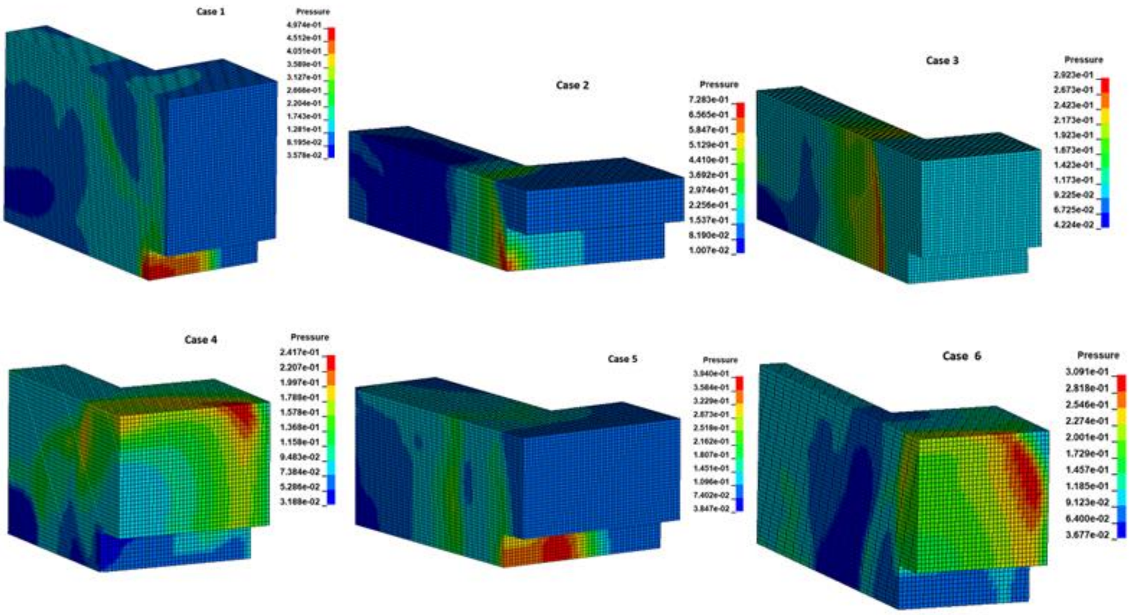

Fig. 46 – Varying Geometries Pressure (MPa) Propagation. Step 6

At this point it can be seen that reducing the volume has different consequences depending on the way it is reduced. Cases with reduced volume 4 and 6 are one step aside the other cases. Case 4 has shorter hall, so it makes sense that propagation occurs fasters, there is less distance to travel. Case 6 is thinner, so higher amount of reflections occurs between lateral walls increasing propagation speed. Case 2, in which volume has also been reduced, does not show this behavior. Pressure front is just about reaching the end step. By reducing the height, since at the top surface there is no wall, apparently no changes in behavior occur.

Finally all cases pressure front end arriving to the end wall step. Then they propagate laterally and finally a phase with several reflections and secondary waves appears until the pressure of the bunker stabilizes again around the initial pressure. But there not major differences in pressure wave behavior for all the different cases from this point until stabilization is reached.

4.3.2 QUANTITATIVE ANALYSIS OF PRESSURE

The distribution of the points under study is the same ones of section 4.1.2 and section 4.2.2. However a brief summary can be found on next figure and table

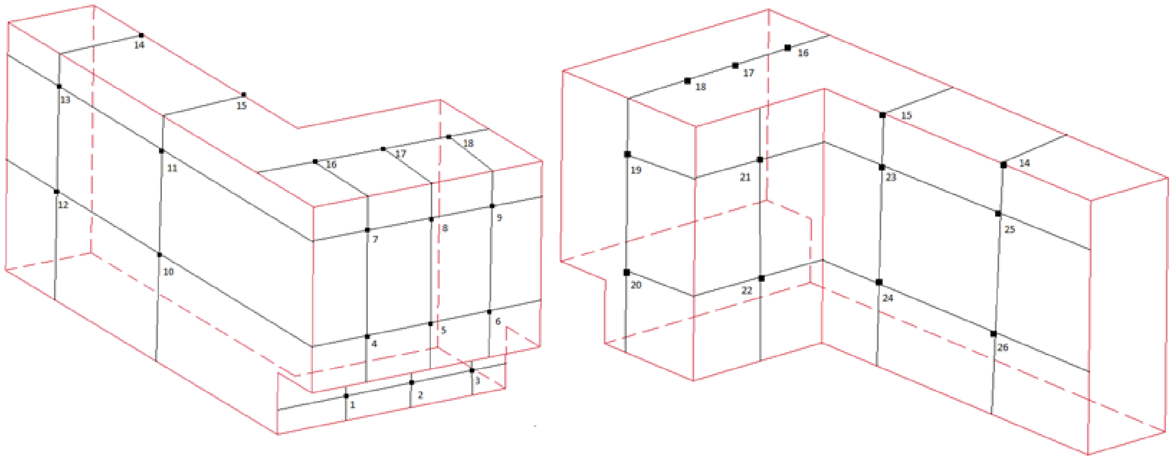

Fig. 47 – Distribution of points under analysis

Set Number	Points inside the set
1	12, 13, 14, 25 ,26
2	10, 11, 15, 23, 24
3	21, 22
4	16, 17, 18, 19, 20
5	1, 2, 3, 4, 5, 6, 7, 8, 9

Table 10- Set of Points under study

Remember that each set of points corresponds to a cross section of the bunker. Being set 1 the cross section located closest to the explosion and set 5 the cross section located furthest from the explosion

Fig.48 corresponds to the cross section closest to the explosion. It can be appreciated a similar behavior in almost all cases. The behavior is also, the same as those seen on section 4.1.2 and section 4.2.2. An initial high pressure peak due to the explosion, then some reflections and stabilization of the pressure. However, in case 2 (low hall), it is possible to appreciate the high pressure peak that was mentioned on previous figures. It appears at the center of the bunker and implies a very high increase on pressure. As it can be appreciated on point 12, this increase can even be higher than the one created by the initial explosion.

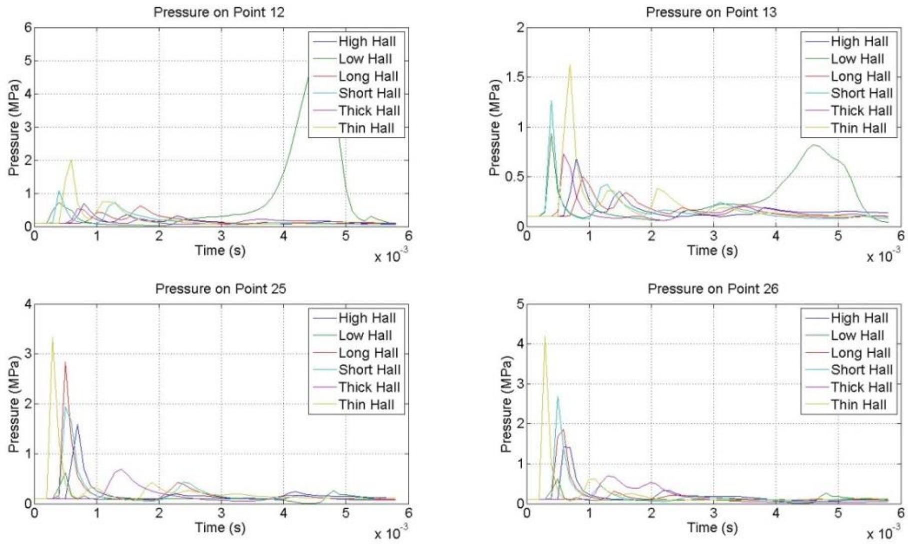

Fig. 48 – Pressure Behavior at Points of Set 1. Varying Geometries Case

Apart from this fact, it can also be appreciated that the geometry that produces the highest pressure peak under the same explosion is the one of case 6 (thin hall) in all the cases, this is due to the higher amount of reflections due to the proximity of the walls. The one with the lowest pressure peak seems to be case 5 (thick hall) at the moment. Case 2, also presents a low value for initial explosion, however the pressure peak produced later, as it will be shown in next section, will be even more dangerous that the initial peaks of other cases.

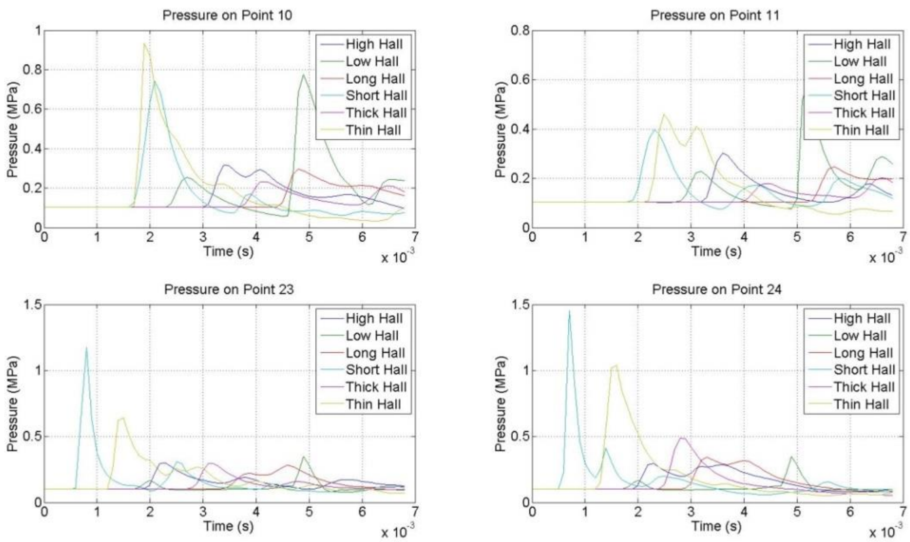

Fig. 49 – Pressure Behavior at Points of Set 2. Varying Geometries Case

On Fig. 49, similar behaviors can be appreciated. The strong pressure peak of case 2 (low hall) is still appreciable. It has a higher influence close to the center of the bunker than on the walls. Also note that the value of the peak at this cross section has been decreased significantly.

Also as stated in the previous section, the cases that seem to be more dangerous for human life are those in which the volume has been reduced. That is, cases 2, 4 and 6 (low, short and thin hall respectively). In Fig. 49 it can be appreciated how the pressure peaks are higher in these cases.

In next figure, Fig. 50 shows the region that is just at the turn of the corner of the bunker. As explained in other sections, this region is quite messy since a lot of reflections occur between this wall and the end wall.

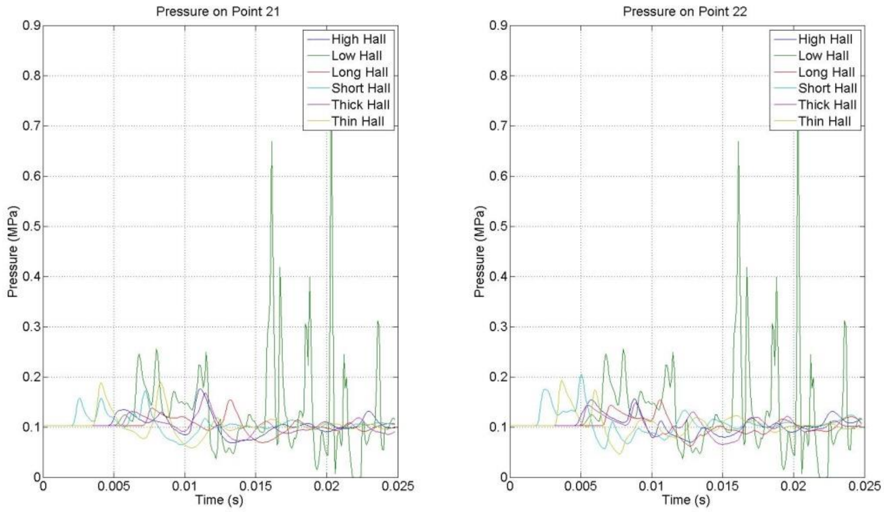

Fig. 50 – Pressure behavior at points of Set 3. Varying Geometries Case

All cases present several oscillations, but note that case 2 oscillations are 3-4 times higher than the rest of the cases. This oscillations also occurs very quick, pressure suffer a high increase and decrease in a very short time. At these points, it is possible to state for sure that the conditions reached on case 2 (low hall) are the worst of all the cases for a human been. It will be also shown in next section using the Head Injury Criteria.

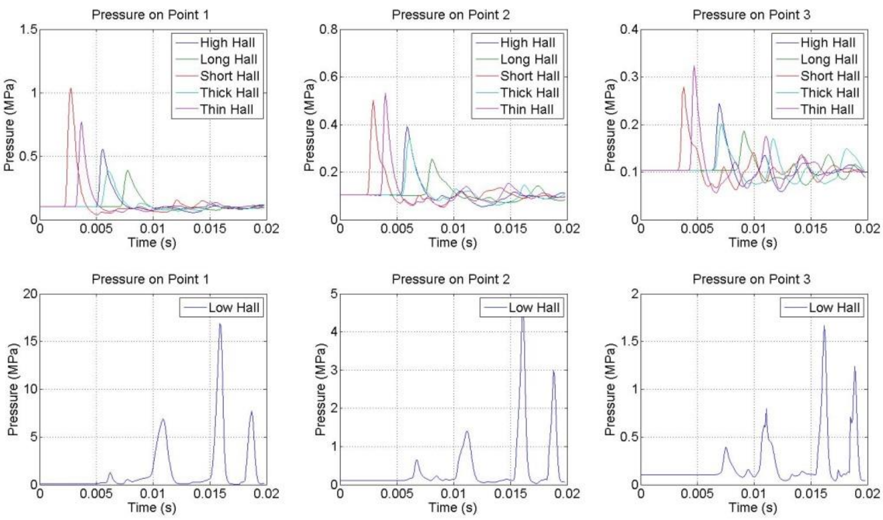

Fig. 51 – Pressure behavior at points 1, 2 and 3. Varying Geometries Case

Now the pressure on the end wall of the bunker is going to be analyzed. Note that the pressure peaks that will appear at this region for case 2 are so high, that it makes no sense to plot it with the rest of the cases, since information could not be seen appropriately.

At Fig. 51 it can be appreciated again that the cases with reduced volume present higher pressure peaks, even double the pressure peak of the cases with increased volume. Also note that the stabilization of the pressure occurs faster for all cases in the points located in front of the explosion. As the point under analysis moves to the lateral of the bunker, the number of reflections increases. But also the value of the pressure peak decreases by one third approximately.

At the end, is the pressure peak the one causing the major injuries, since high change of pressure are produced in small times, therefore creating high accelerations, the main input of Head Injury Criteria.

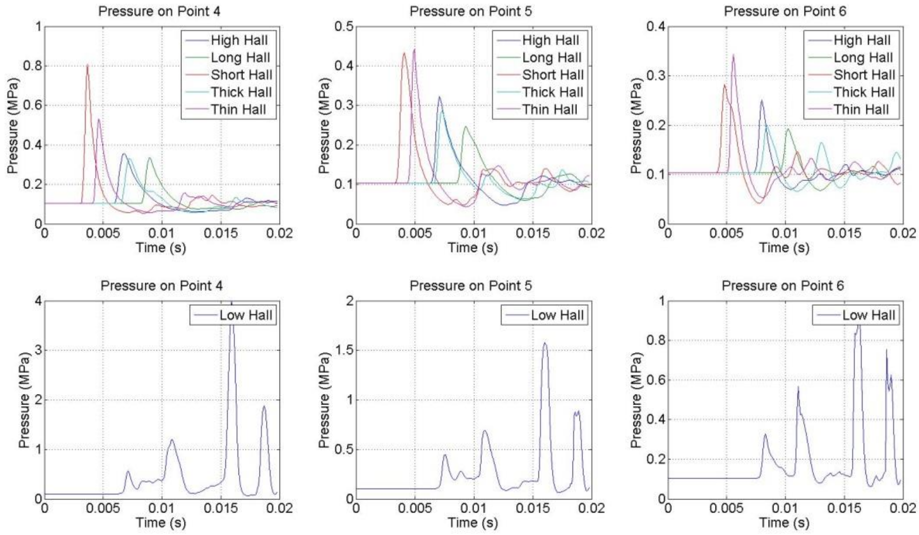

Fig. 52 – Pressure Behavior at Points 4, 5 and 6. Varying Geometries Case

In Fig. 52, the same behavior can be appreciated as the point is located more to the lateral. The important thing to note compared to Fig. 51 is that, as the height is increased, the pressure peaks decrease. Point 4, which is located above point 1, presents lower pressure peaks for all the cases. The same relation applies to points 2 and 5, and to points 3 and 6. Finally, at Fig. 53 the same behavior can be observed for points 7, 8 and 9.

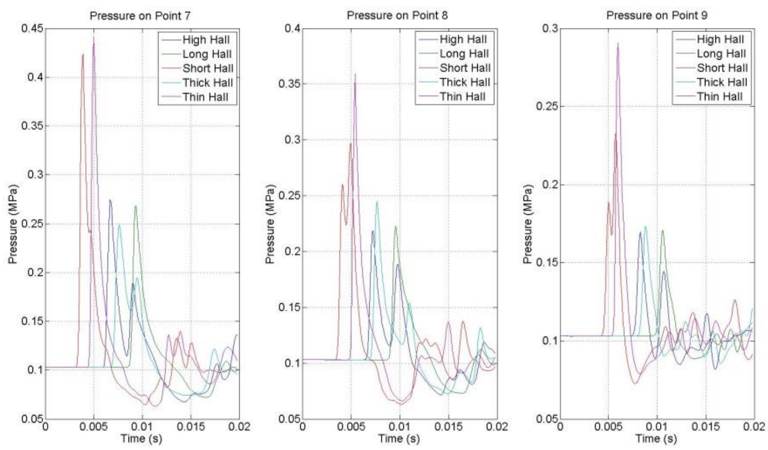

Fig. 53 – Pressure Behavior at Points 7, 8 and 9. Varying Geometries Case.

4.3.3 HEAD INJURY CRITERIA ANALYSIS

When analyzing the head injury criteria on different points of the bunker it was sadly discover that again there is no location in the bunker where human been survival is possible. Nevertheless, this fact does not mean that a critical analysis can't be done.

With the following data it is possible to figure out what of the studied geometries represents a better choice and it is closer to allowing a human been to survive to such an explosion. At least it is possible to state the way that must be followed in order to achieve the final goal.

As done in previous sections HIC will be analyzed at different cross sections of the bunker, each cross section composed of several points at different positions, as exposed in section 4.3.2

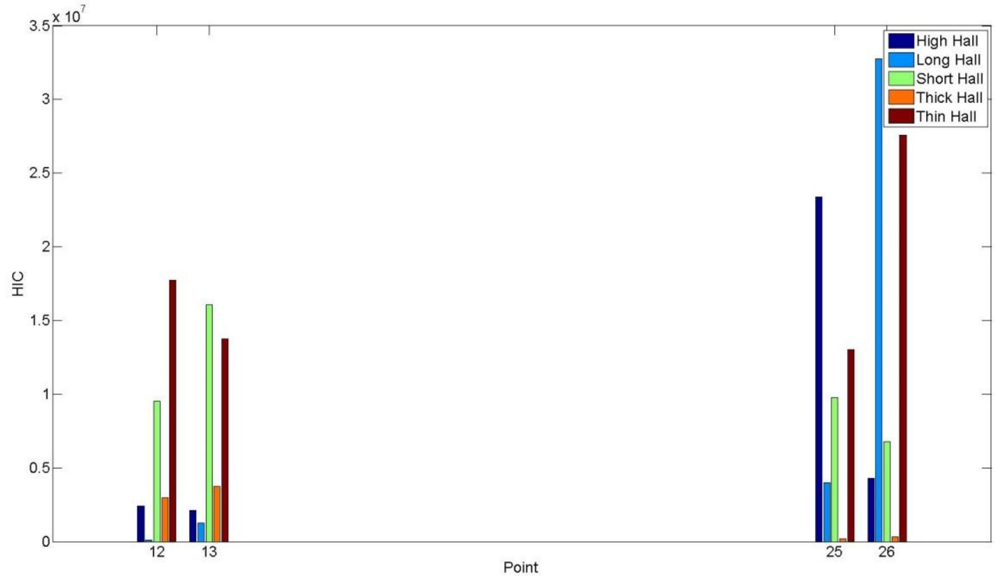

Fig. 54 – HIC value at Points 12, 13, 25 and 26. Varying Geometries Case

This first image shows the cross section that is closer to the point of the initial explosion. First of all, remark that close to the lateral wall (points 25 and 26) the HIC tend to increase. Since air encounters here a medium through which it can't propagate, a collision occurs and air is even more compressed in this region, therefore creating higher accelerations and so higher HICs.

The other main thing to note is that cases that present increase volume (High Hall, Long Hall and Thick Hall) usually present smaller values for HICS since propagation and pressure distribution occurs much more smoothly due to higher space air has to do it. This will be better appreciated later, since these points are so close to initial explosion that not even the pressure front has developed yet, it is a transient region where strange behaviors may appear.

It is also important to remark that the distribution of the points under analysis has been done to cover the whole bunker space. However, just single points are being analyzed. If due to geometry and pressure reflections, at any of these points there is a high pressure peak, an abnormally high HICs may appear.

This does not mean that computations are wrong. But only that for those particular geometries, at those particular points it would be extremely dangerous for a human been to be there, since the pressure wave and accelerations are particularly strong there.

For instance, this must be the case at points 23 and 24 for the short hall geometry configuration.

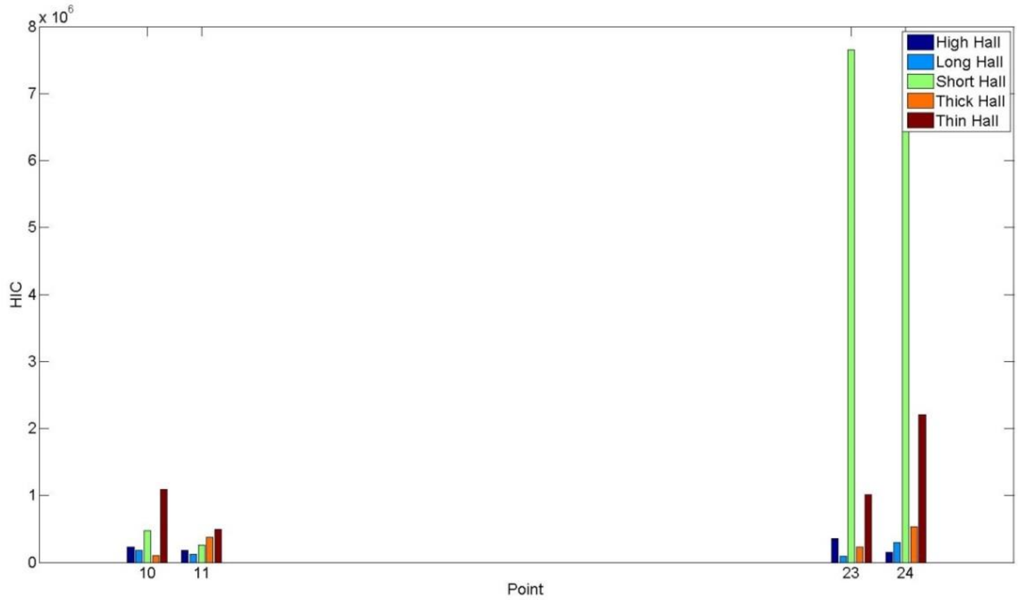

Fig. 55 – HIC value at points 10, 11, 23 and 24. Varying Geometries Case

From the previous two figures it looks like for the hall section of the bunker, the best geometry, the one that produces in general the lower HICs is the thick hall geometry configuration. Due to the smoother pressure propagation it has been exposed before on this section.

Immediately after the turning on the corner the behavior observed is similar. The cases with reduced volume present more dangerous situations for human beings than the ones in which the volume has been increased.

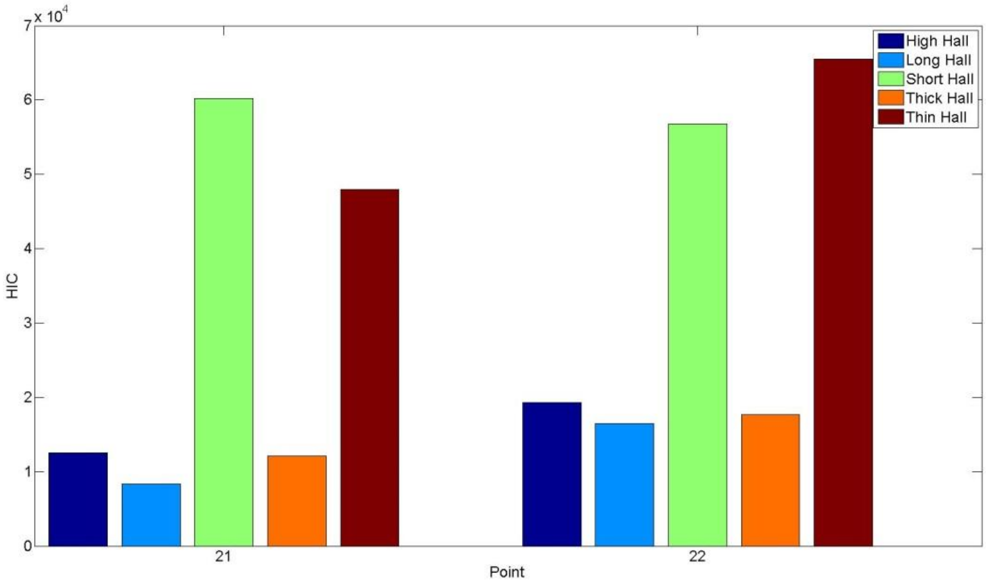

Fig. 56- HIC value at points 21 and 22. Varying Geometries Case

Again the same for the next cross section. But using these last two figures, it is possible to arrive to a new conclusion. It looks like, the criticality of the explosion decreases as the height is increased.

Points 16, 17 and 18 are located at the roof of the bunker, at it can be clearly seen that its HICs value, for all the geometries is lower than those calculated at point 19, which is slightly lower than the previous 3. And much smaller than the HICs value calculated on point 20 which is just slightly above the floor.

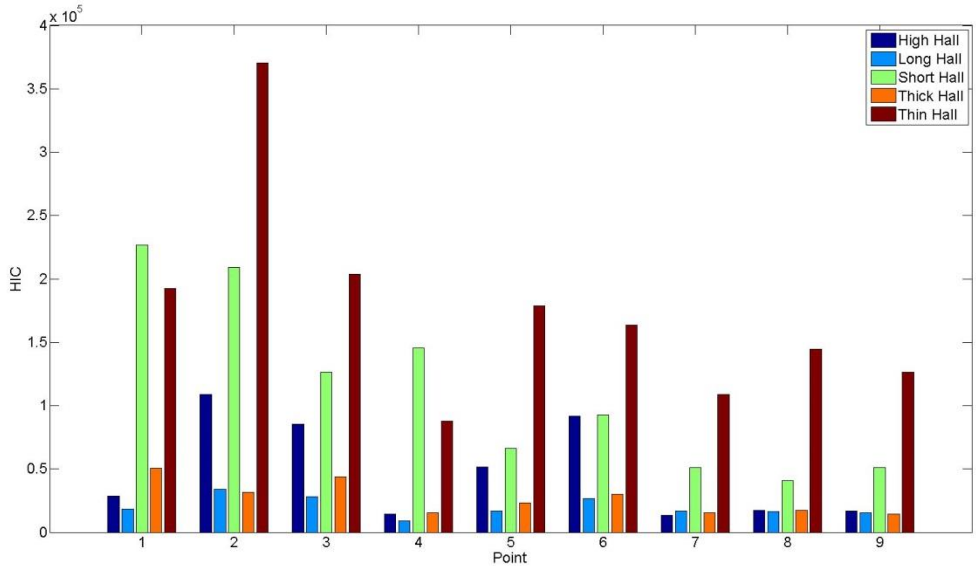

Fig. 57 – HIC value at points 1, 2, 3, 4, 5, 6, 7, 8 and 9. Varying Geometries Case

In the points located at the end wall of the bunker, this last idea is confirmed. Since at points located at higher heights the HICs is reduced.

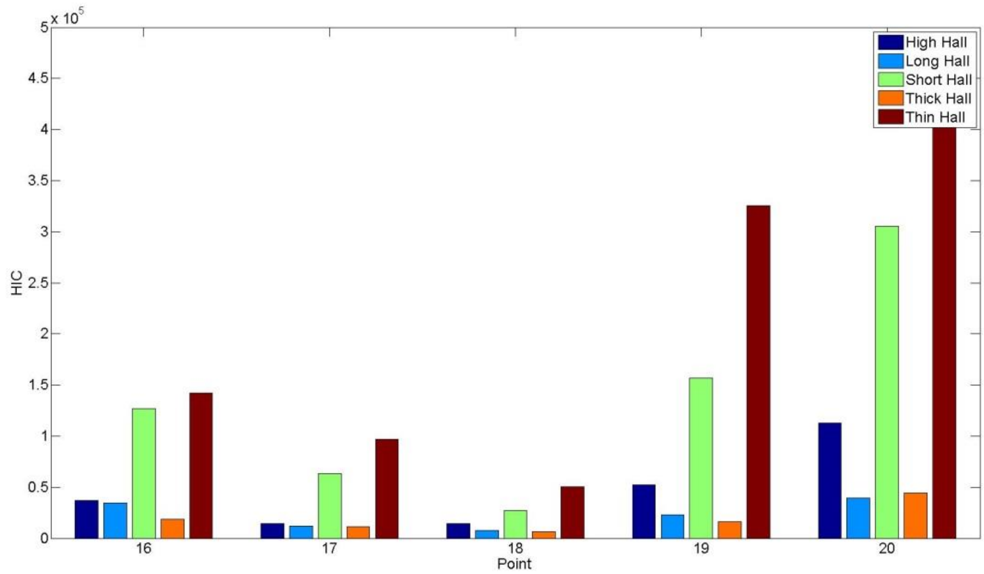

Fig 57 – HIC Value at points 16, 17, 18, 19 and 20. Varying Geometries Case

As a pre-conclusion from all this information, between all the studied cases the most favorable for a human been to survive will be one with and increased volume respect the original one, in particular the one with thicker hall due to the smoothness of it pressure propagation.

In addition to that, if the human been should be standing up, in order to have its head at the higher height possible. If possible, standing up on the step on the end wall.

5 SENSITIVITY ANALYSIS

This section is done in order to have an idea of the validity of the results obtained and the influence of the mesh on these simulations. Since, as stated in section 2.2, defining the mesh is one of the main issues when working with Finite Element Method. In Fig. 59 the different mesh configurations used for this analysis are shown:

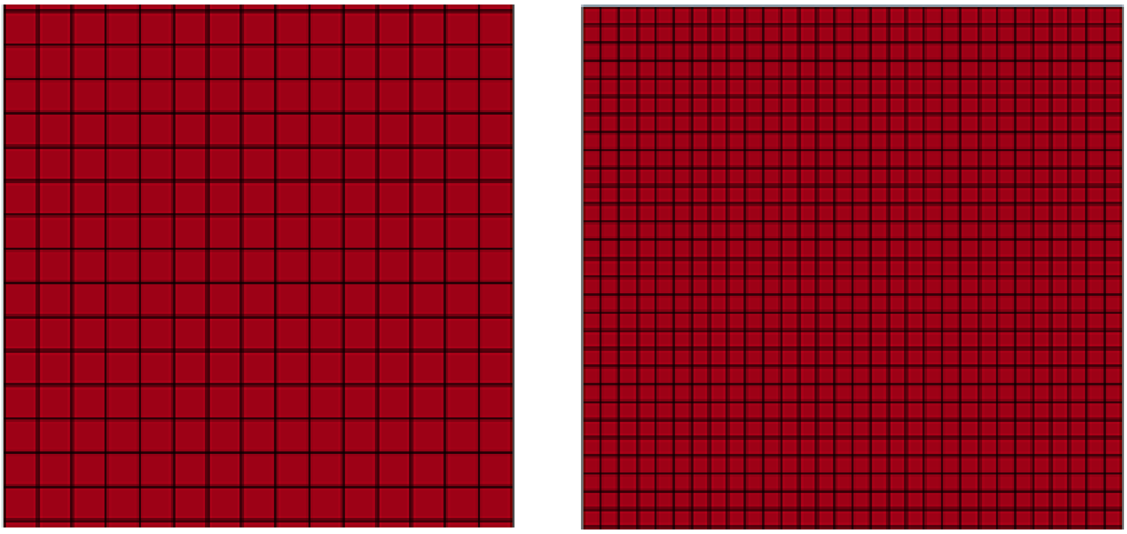

FIG. 59- Mesh comparison

At the left of Fig. 59, the original mesh is show. The one with which all previous computations have been done. On the right, the finer mesh. This mesh presents the same element geometry as the original one, that is, in both cases the elements are cubes. However the finer mesh elements dimensions are half in each of the directions. That is, inside an element of the original mesh there are 8 elements of the finer. To sum up, the finer mesh presents 8 times more elements than the original one.

One may think at this point, since the finer mesh present so much more elements the results obtained by using this mesh will be more accurate, so why it is not used in the previous computations? The answer is just about computational costs. Reproducing all the previous cases with the finer mesh would take too many resources, being the one more restrictive time. Since a case computed with original mesh took about 15 minutes to run completely, but the one computed with the finer mesh took around 40 minutes to be completely computed

Also note, that this work is mainly focused on comparing different cases to see what is the less dangerous for humans. So if even with the original mesh there are some deviations from reality, these deviations exist for all cases, so it will still be valid to make a comparison. Once this comparison is made, and it is clear what is the case or cases that are interesting to study more in detail, a computation of these cases with the finer mesh shall be done in order to obtain the most accurate results possible. However, since this work does not reach that point, the finer mesh was decided not to be used, in order to save computational resources and time, and still obtaining valid conclusions.

Both cases under analysis present the same trench geometry and the same location of the explosive, both corresponding to the model explained in Section 4. Since the only thing changing between the two cases studied here is the mesh, the behavior of pressure wave propagation found is the same. This behavior is explained in Section 4, and it is not going to be repeated here.

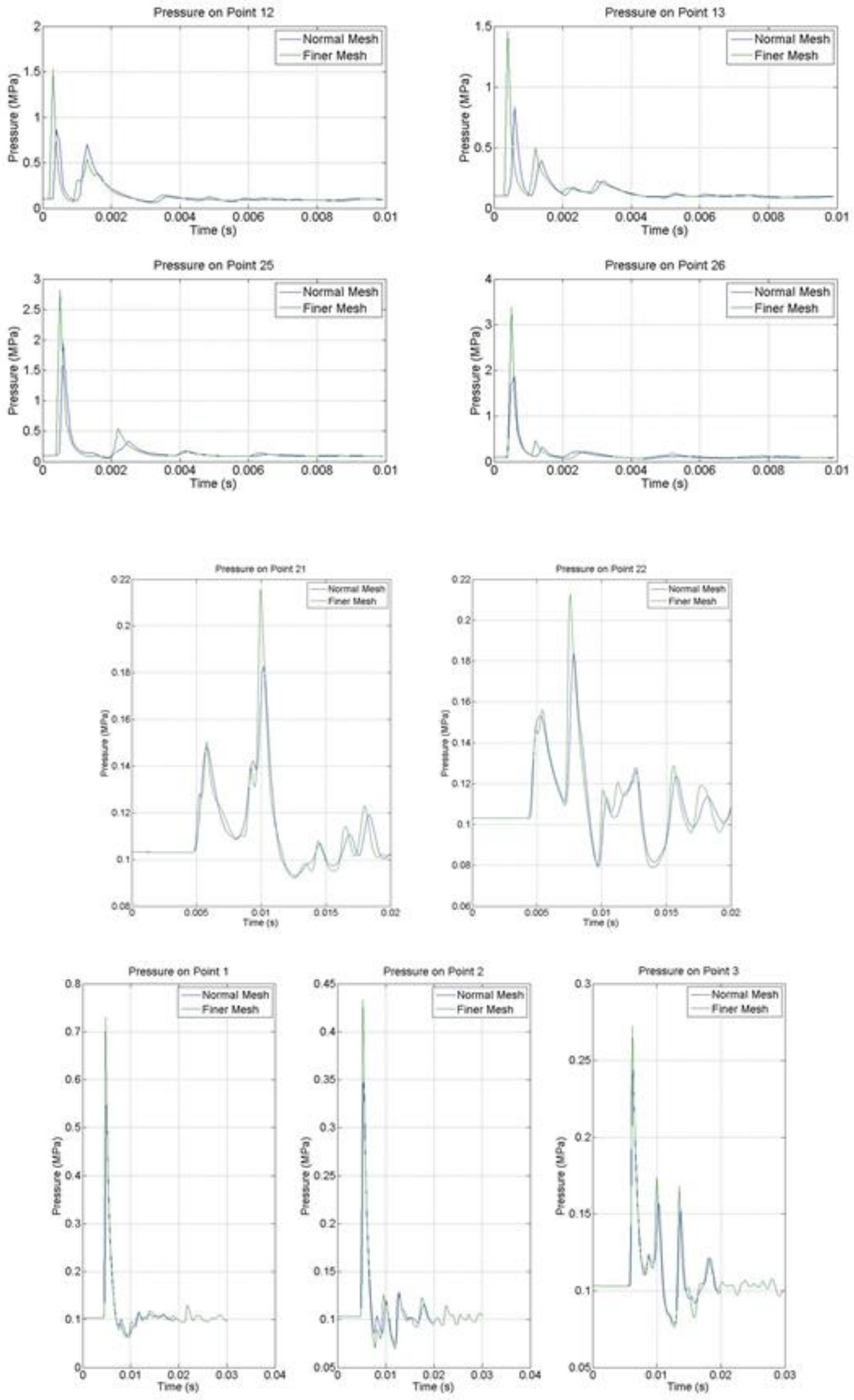

FIG. 60 – Pressure Comparison for different meshes at several points of the bunker

In previous Fig. 60, several points of different location of the bunker have been represented. This set of points is enough in order to see the influence of the mesh on the results. As it can be appreciated, the behavior is identical at all points. There is only one main difference when using one mesh or another.

When using the finer mesh, higher pressure peaks are obtained at all points. That is the main remarkable difference in between these two meshes. That means that in all previous studied cases, pressure values are under-estimated. It really does not matter, since all the studied cases end up being mortal for a human being. But careful shall be taken if some case were found not to be mortal, since the results are under-estimated and in reality the case could be as mortal as the other. If that were the case in this work, a finer mesh analysis should have been done in order to ensure that surveillance is real, and not just a computational matter.

Similar conclusion can be obtained from the HICs graph, the cases with the finer mesh always present higher HICs value than the original mesh, as it can be seen in Fig. 61

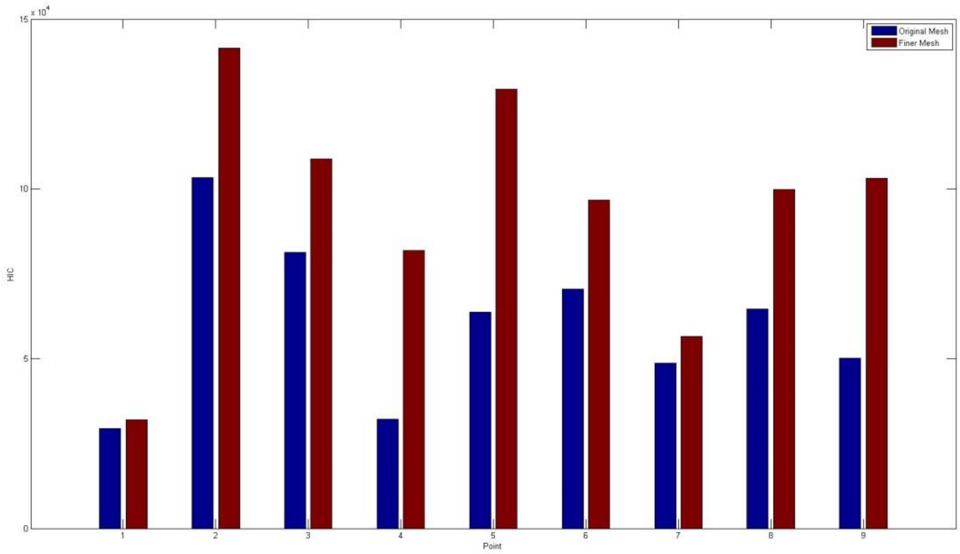

Fig. 61 – HIC comparison for different meshes at points 1, 2, 3, 4, 5, 6, 7, 8 and 9

Again not all the plots at all points are going to be displayed since it is only of interest to check the difference between both cases, not the values itself. And the behavior shown on Fig. 61 is repeated in all points of the trench.

6 CONCLUSIONS

After all the analysis, unfortunately no point where human being surveillance is possible was found. However, this analysis can be used to extract some interesting conclusions that can point the way through which this study shall be continued. During the explanation of these conclusions, the points located immediately close to the explosion will not be taken into account, since at these points conditions are extremely critical for humans. These conclusions are here summarized:

- From base model analysis, it was found that the point which is more dangerous for human beings is placed at the part of the step located in front of the explosion. Close to point 1 of Fig.47. In terms of pressure and HICs, it is probably the most dangerous place for a person to be. It could exist the case where a soldier was sitting at this location just waiting, and for sure it was not a good idea in case an explosive goes into the bunker.

- Also it was found from base model analysis that close to walls or close to the floor the pressure peak increases and the HIC is more severe. This is due to ground effect, air can propagate thought the wall and it is compressed against it, therefore increasing its pressure. It can also be seen from an energy point of view. The air arriving at the wall has to reduce its velocity, therefore is kinetic energy and this traduces intro an increase of pressure.

- Finally it was found that due to the geometry and the reflections behavior, the point where it is more likely that a human survives is at points 18 and 21 if Fig. 47. Just in the region close to the top surface when turning the corner, the pressure peak is the lowest and also the HIC. According to previous conclusion, it is even better at point 18 since it is not at the wall.

- Regarding the location of the explosive it was found form previous analysis that consequences are more severe when the explosive is located at the floor. Again, this occurs due to the proximity to the floor and the ground effect. Reflected pressure wave presents a higher pressure peak. On the other hand, the most benevolent explosive location is upwards, as far as possible from the ground, and even better if it is located away from the lateral walls. That is, the best location is centered upwards.

- Respect the different geometries analyzed, a major conclusion was obtained. The cases where the volume of the bunker was increased, present better conditions for humans (even if they are still mortal). In particular, the best case is the one in which the thickness was increased. It totally make sense, since lateral wall are separating in this case.

- As major conclusion, it seems that the effects of the blast tend to be less severe as the explosion approaches to a free air explosion, where no walls exist. The existence of wall, generate ground effect along the bunker, increasing the pressure compare to a free air explosion. That is why the case where the better conditions for surviving shall be found would be a thick bunker, where the lateral walls are separated as much as possible. Also, the explosive should be located upwards and centered, as far as possible from the ground and the walls. Finally even if this case is the best possible of those that have been studied, not at all the points of the bunker the same conditions will be found. The best location under this scenario (and all scenarios in fact) is, as said before, close to point 18 of Fig. 47.

- Additionally, from sensitivity analysis it can be conclude that for all the cases, the pressure and HIC values are under estimated. That is, the real one will be above the ones obtained in the simulation. That is a very important point to take into account, if more detailed analysis were done.

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